History of Stellar Interferometry

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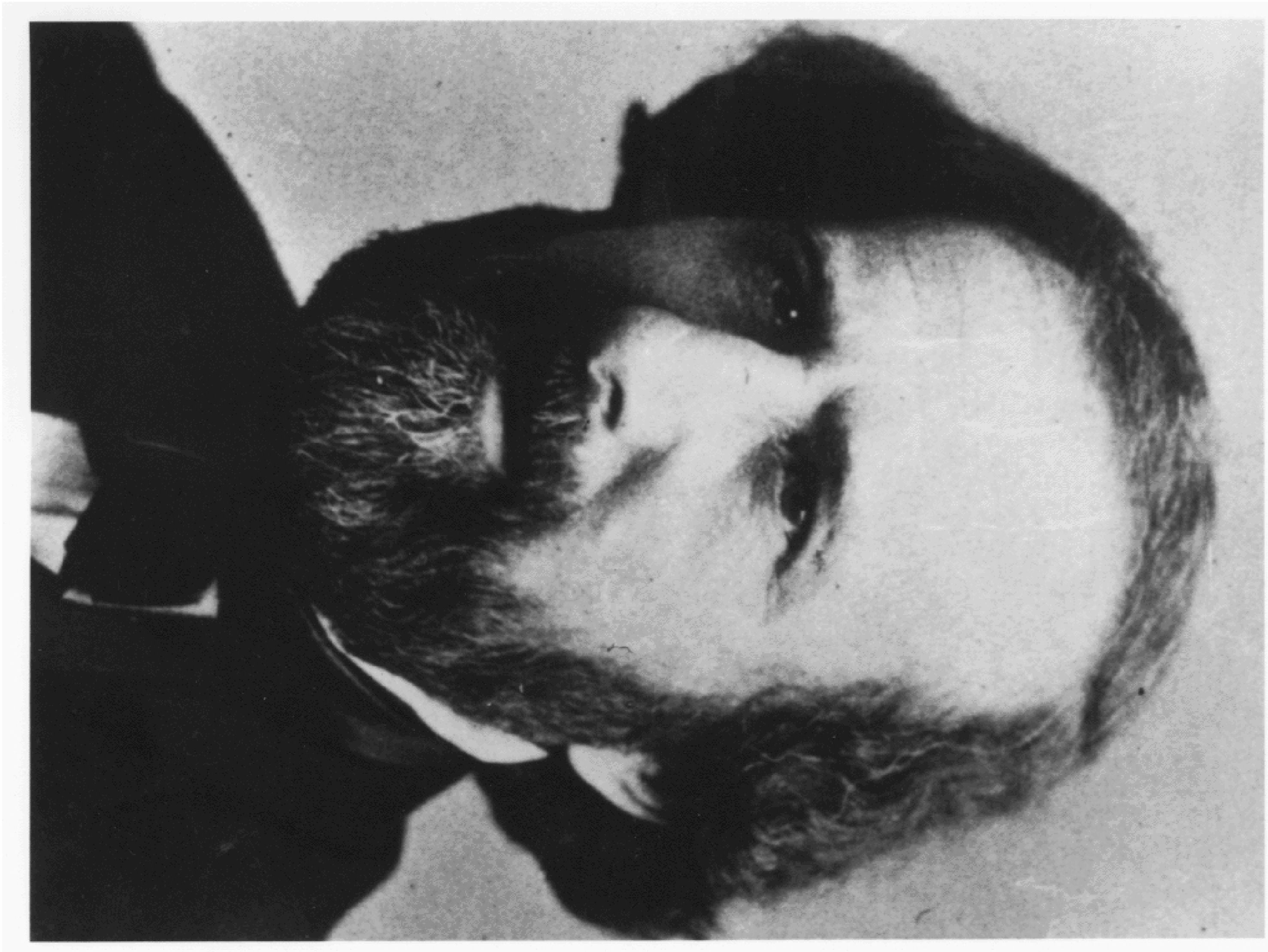


PRIX BORDIN.

QUESTION PROPOSÉE EN 1865 POUR 1867.

(Commissaires : MM. Duhamel, Pouillet, Regnault, Bertrand, Edmond Becquerel, Fizeau rapporteur.)

Rapport sur le Concours de l'année 1867.

« Le prix sera décerné au savant qui aura exécuté ou proposé une expérience » décisive permettant de trancher définitivement la question déjà plusieurs fois » étudiée de la direction des vibrations de l'éther dans les rayons polarisés. »

Il existe en effet pour la plupart des phénomènes d'interférence, tels que les franges d'Yung, celles des miroirs de Fresnel et celles qui donnent lieu à la scintillation des étoiles d'après Arago, une relation remarquable et nécessaire entre la dimension des franges et celle de la source lumineuse, en sorte que des franges d'une ténuité extrême ne peuvent prendre naissance que lorsque la source de lumière n'a plus que des dimensions angulaires presque insensibles; d'où, pour le dire en passant, il est peut-être permis d'espérer qu'en s'appuyant sur ce principe et en formant par exemple, au moyen de deux larges fentes très-écartées, des franges d'interférence au foyer des grands instruments destinés à observer les étoiles, il deviendra possible d'obtenir quelques données nouvelles sur les diamètres angulaires de ces astres.

H. Fizeau (1819-1896)
E. Stephan (1837-1923)

- **1868 Fizeau suggests the possibility of stellar interferometry.**
- **1874 E. Stephan uses the Foucault telescope at the Marseilles Observatory to observe most stars down to 4th magnitude.**
  - **65 cm aperture separation.**
  - **All stars produce distinct fringes.**
  - **Concludes stars must have diameters much smaller than 0.158 arcseconds.**
- **1896 M. Hamy performs similar measurements at the Observatoire de Paris.**

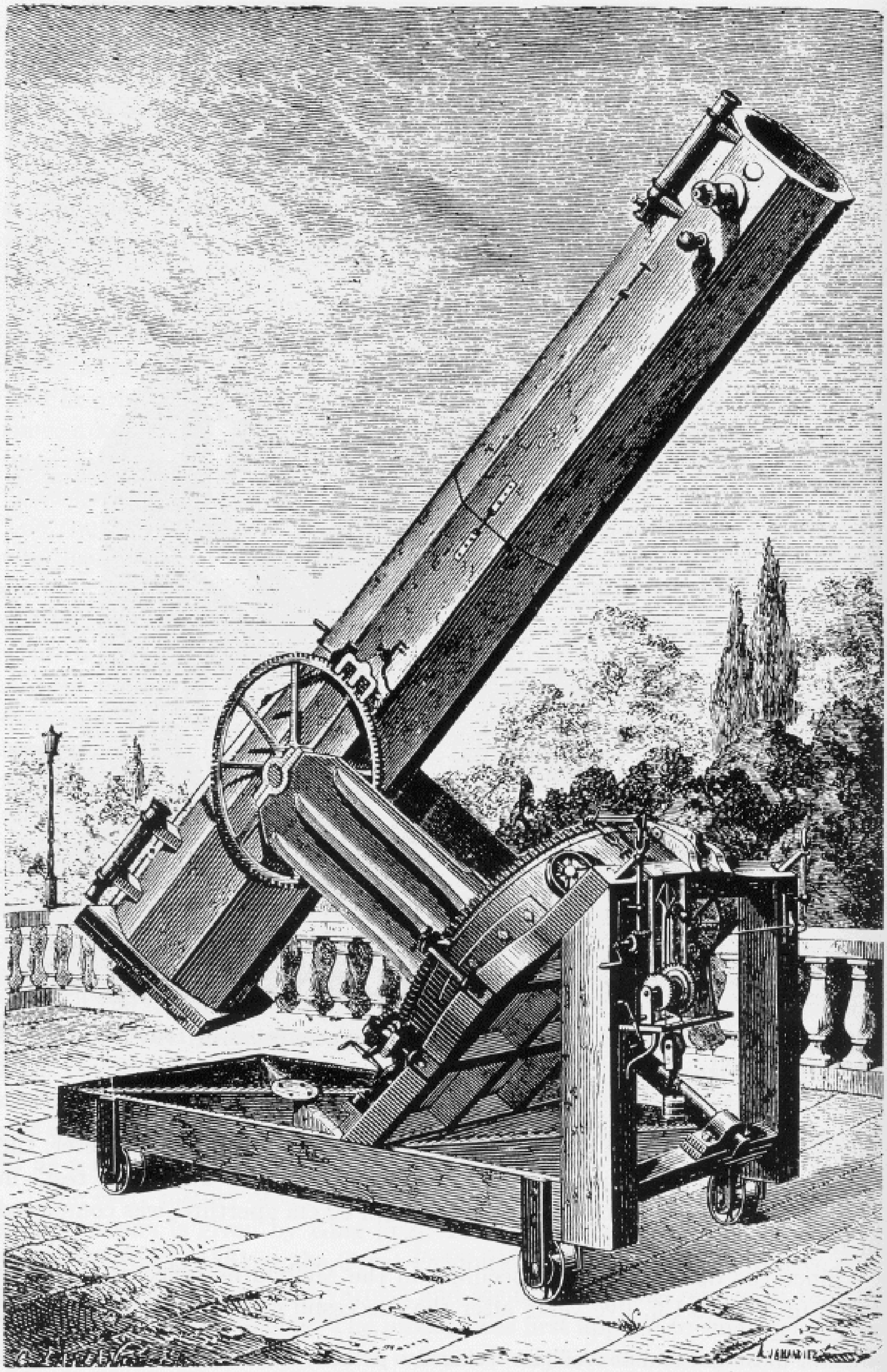
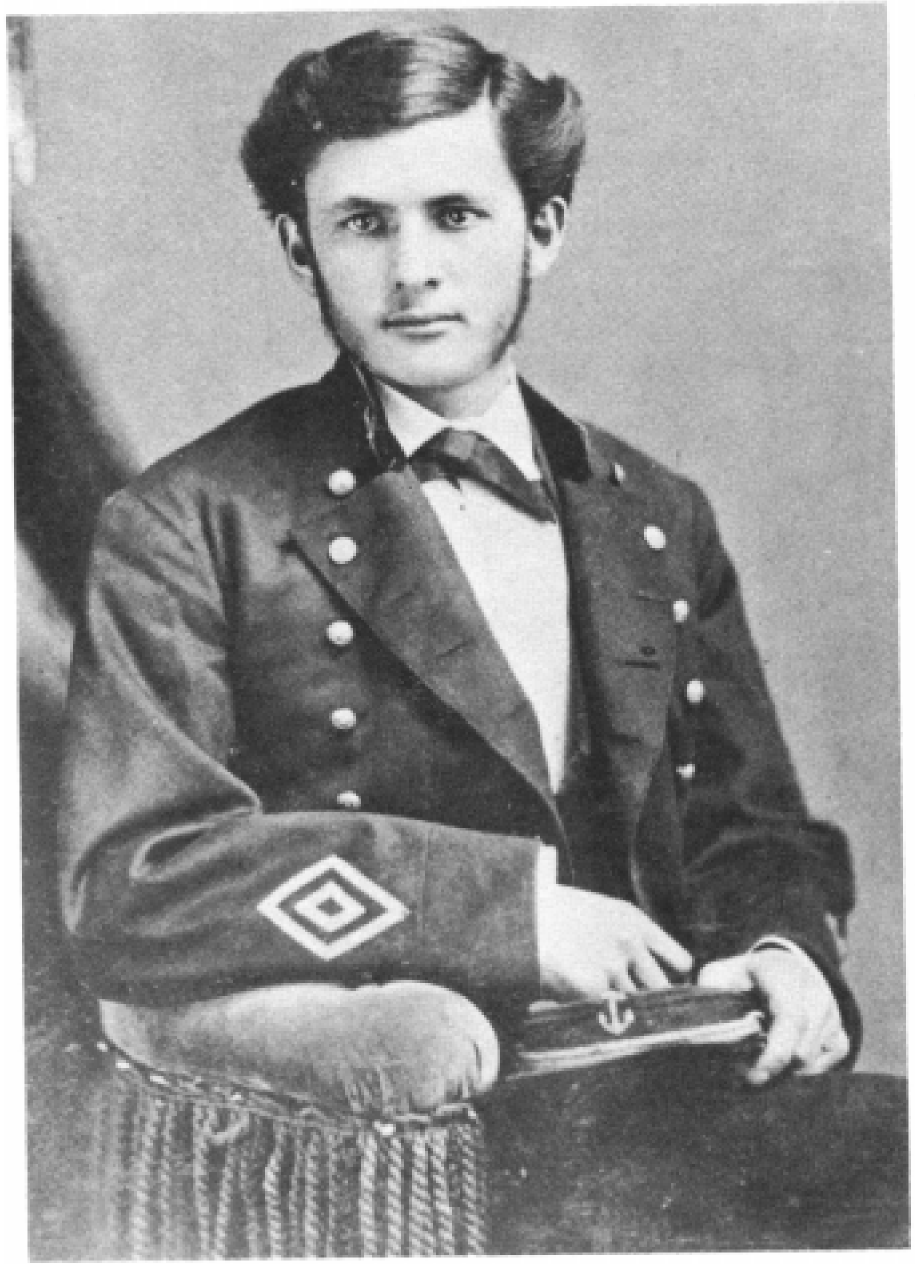
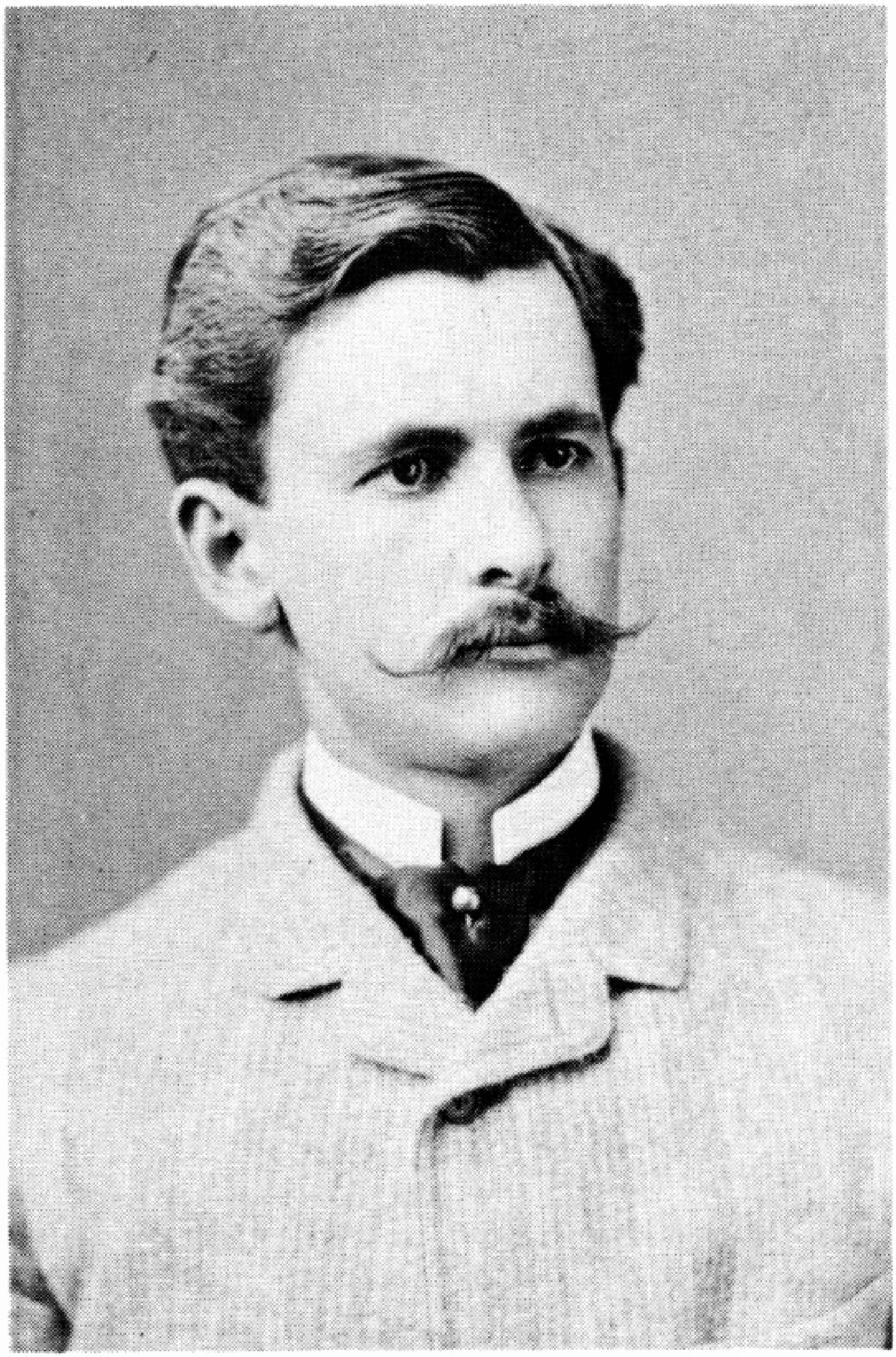


Fig. 5.8. Foucault's largest (80 cm) silver-on-glass reflector, completed in 1862 (reproduced from King [5.2])

Albert A. Michelson (1852-1931)

- **1878. Measures speed of light 200 times more accurately than previous measurements.**
- **Invents *Interferential Refractometer* 1880 in Berlin while on leave from Naval Academy.**
- **1887. Michelson-Morley experiment.**
- **1890. Describes mathematical basis of stellar interferometry.**
- **1891. Measures Jupiter's moons.**
- **1907. Receives Nobel Prize in physics.**
- **1920. Measures diameter of Betelgeuse with the 20 ft Interferometer.**

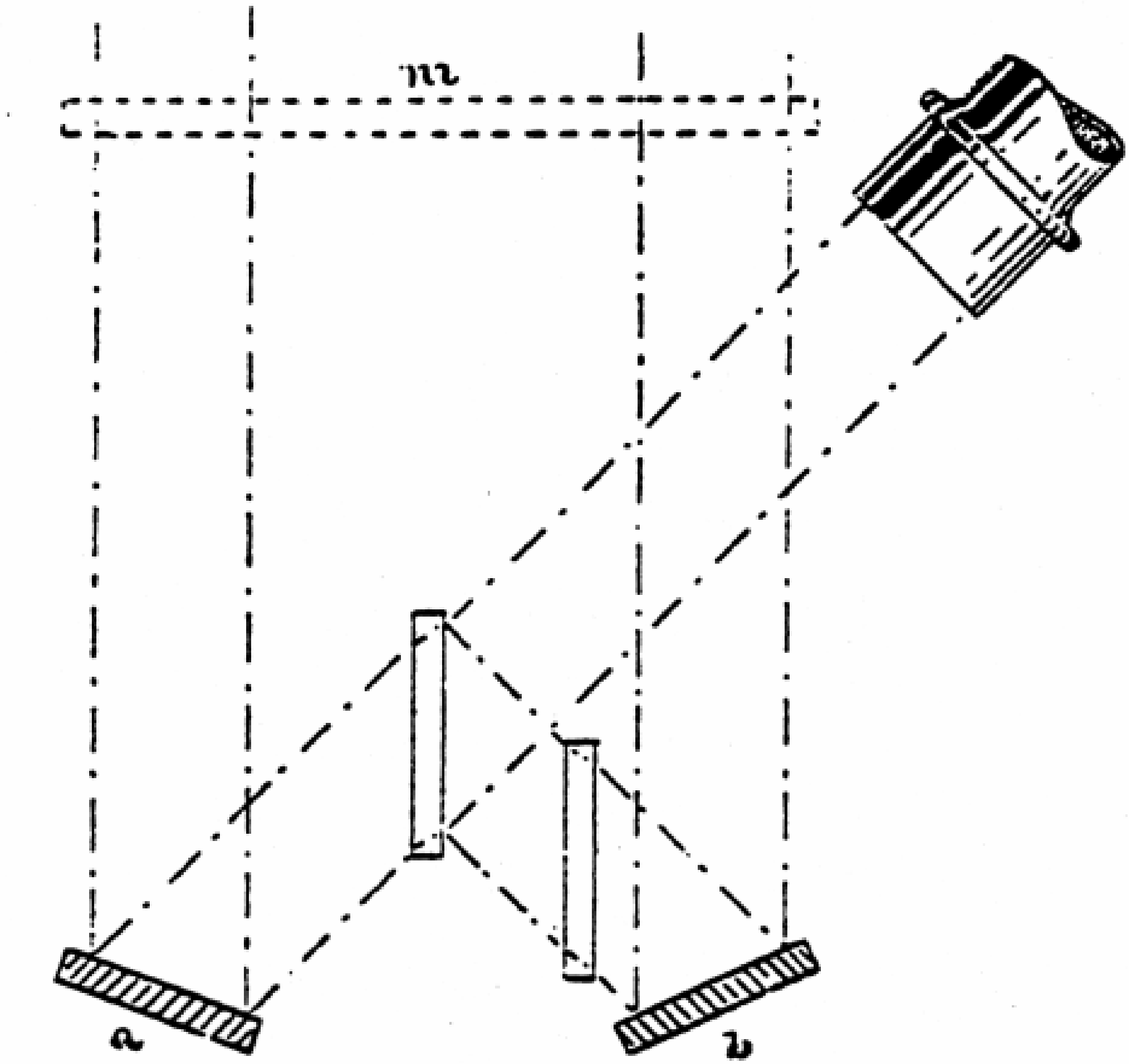




Michelson in 1887, at the time of the Michelson-Morley experiment (COURTESY CLARK UNIVERSITY ARCHIVES)

The interferometer had performed with marvelous accuracy, and its beauty consoled Michelson to some extent for the negative result. He began to think of new fields where this technique might apply. Like Pygmalion, he became enraptured with his own creation. Theoretical physicists as a rule do not experience this emotion and are therefore inclined to belittle it. But Galileo knew the feeling and voiced his exultation over the marvels of his telescope with a similar joy:

"O telescope, instrument of much knowledge, more precious than any sceptre! Is not he who holds thee in his hand made king and lord of the works of God?"[23]


m
a
b

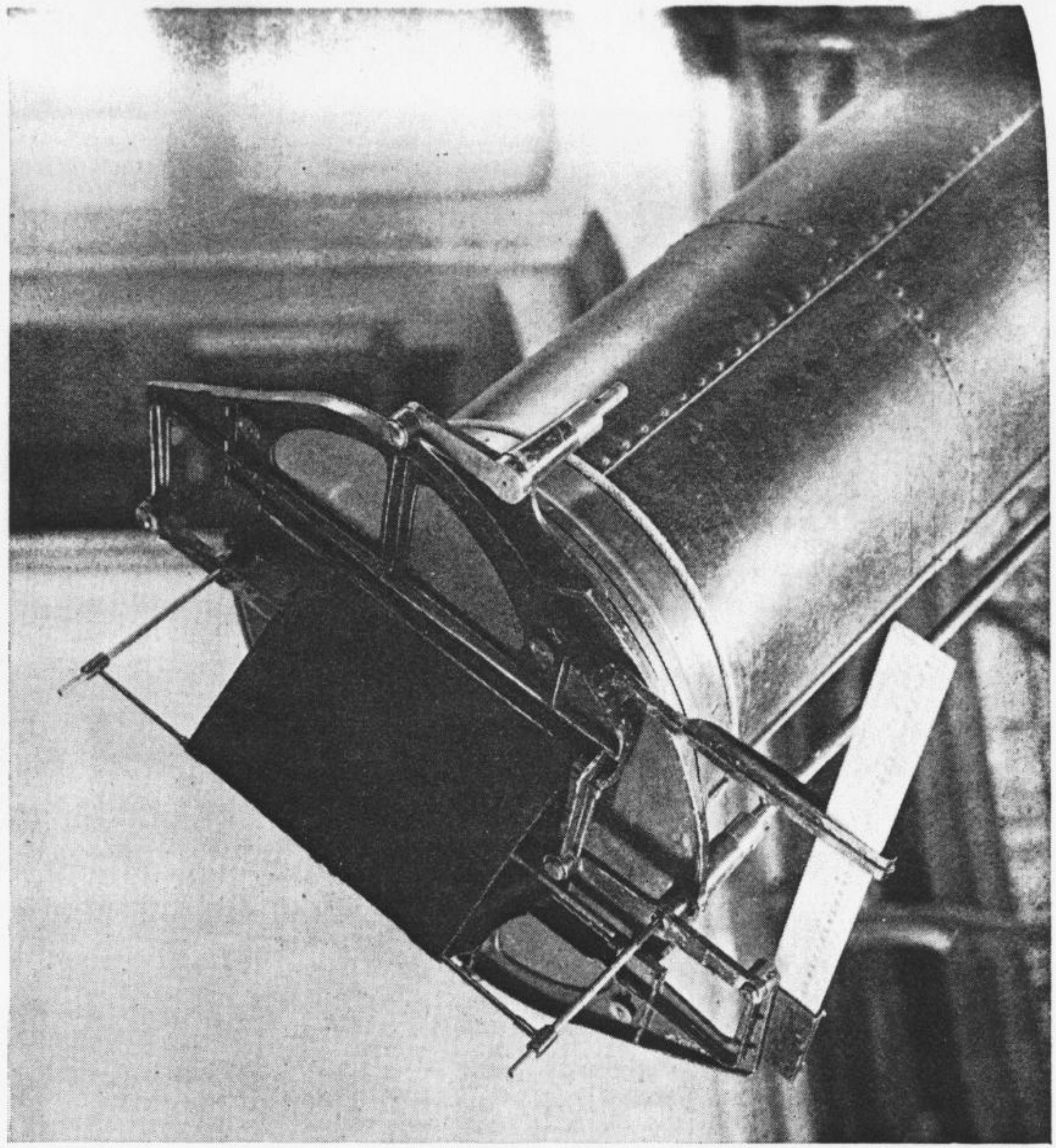
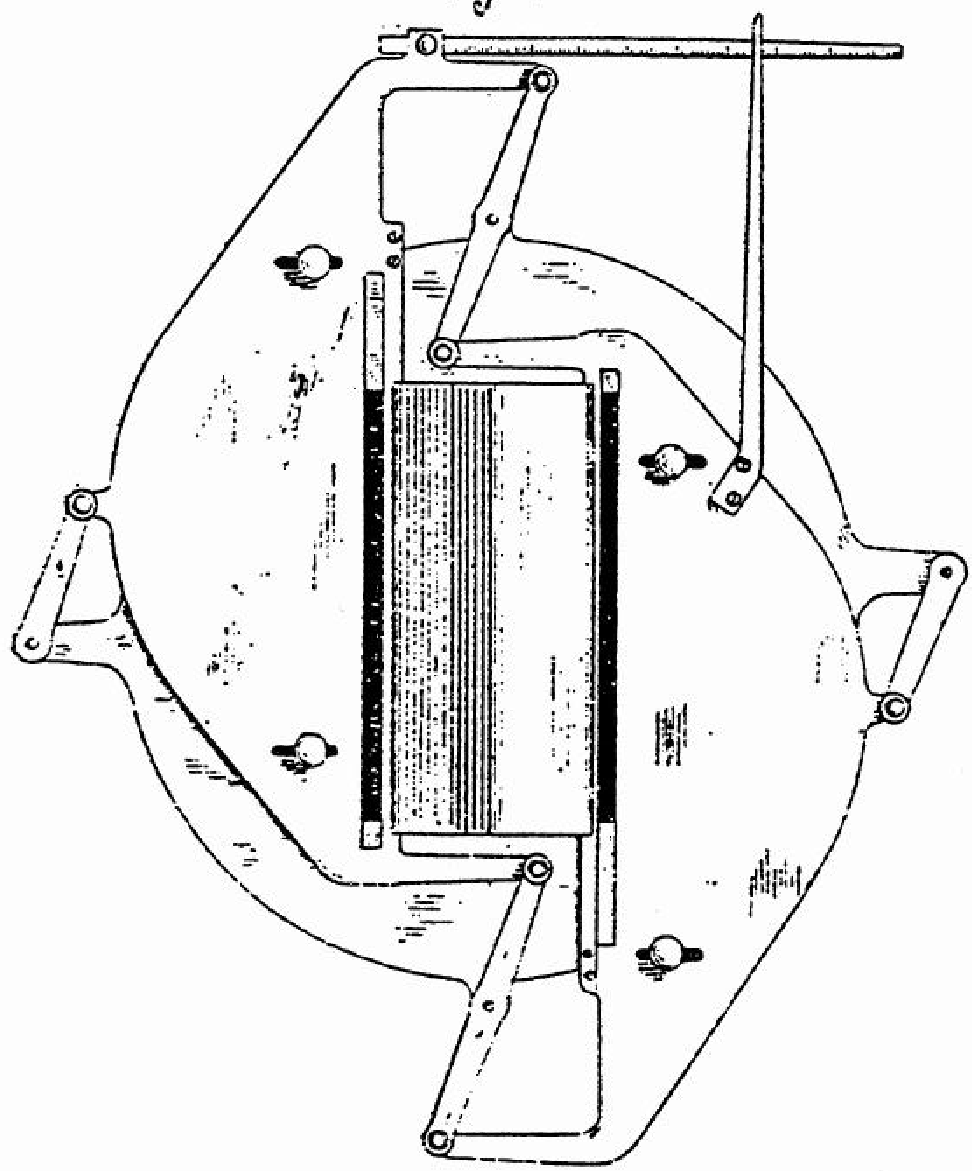


FIG. 1. Interferometric mask used on the 12-inch refractor at Lick Observatory to measure the angular diameters of the Jovian satellites. The rod adjacent to the telescope tube is turned by the observer, which in turn rotates a lever connecting the two slits immediately exterior to the pictured objective shroud. Photograph courtesy University of California at Santa Cruz Library.

Fig 3



With this apparatus the satellites of Jupiter were measured, with results as given in the following table :—

TABLE I.

No. of Satellites.	I.	II.	III.	IV.	Seeing.
August 2	1″·29	1″·19	1″·88	1″·68	Poor.
August 3	1·29	—	1·59	1·68	Poor.
August 6	1·30	1·21	1·69	1·56	Poor.
August 7	1·30	1·18	1·77	1·71	Good.
Mean...	1·29	1·19	1·73	1·66	

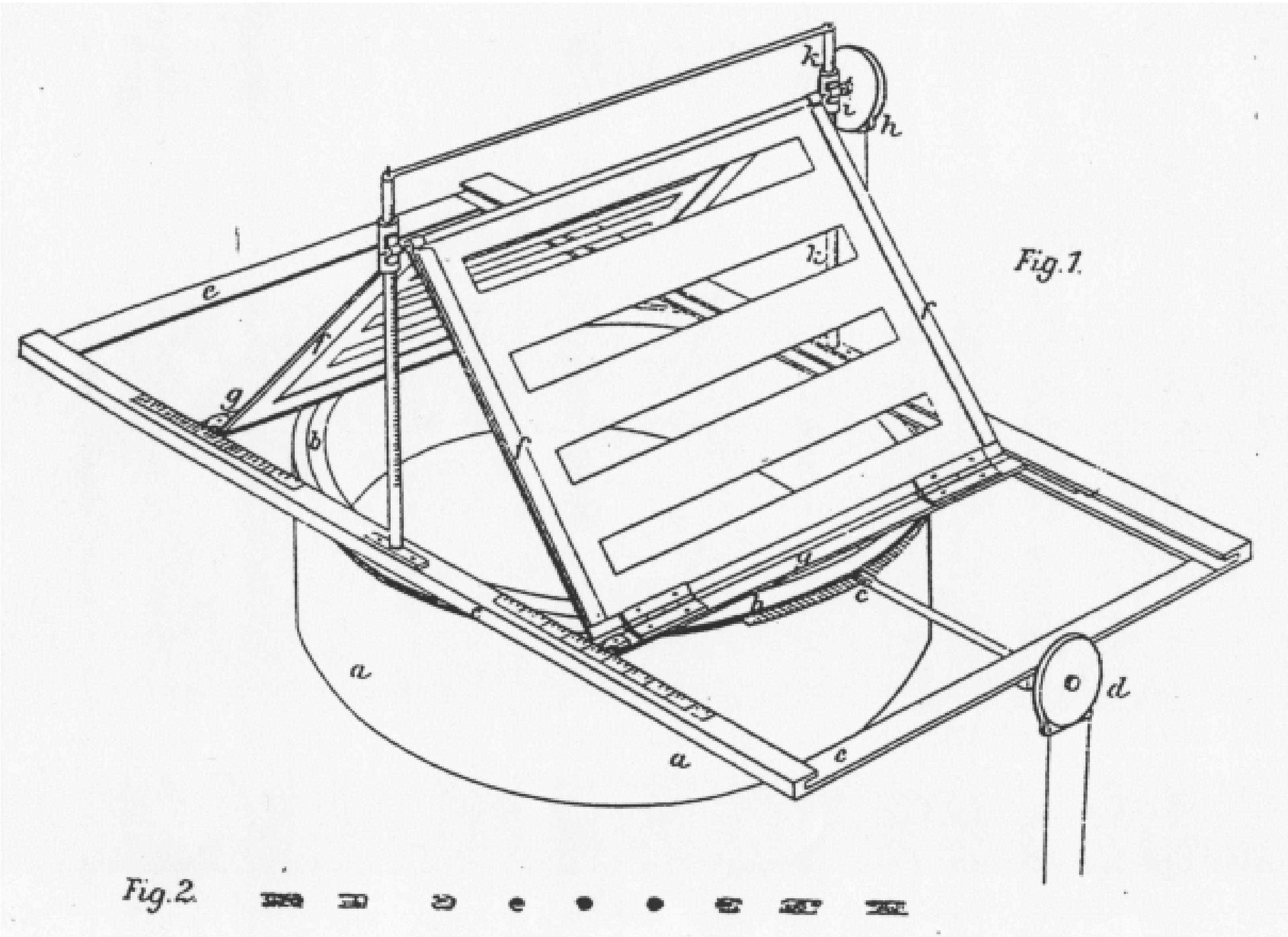


Fig. 1.
Fig. 2.

Karl Schwarzschild
Born: 1873, Frankfurt/Main, Germany
Died: 1916, Potsdam

In 1905 Schwarzschild formulated the complete third order aberration theory of 1- and 2-mirror telescopes. Furthermore, his formulation can be extended to any system and forms the basis of all modern reflecting telescope optics. He also developed a practical "Eikonal" theory giving the total aberration at a given field point. (Courtesy Martin Schwarzschild)

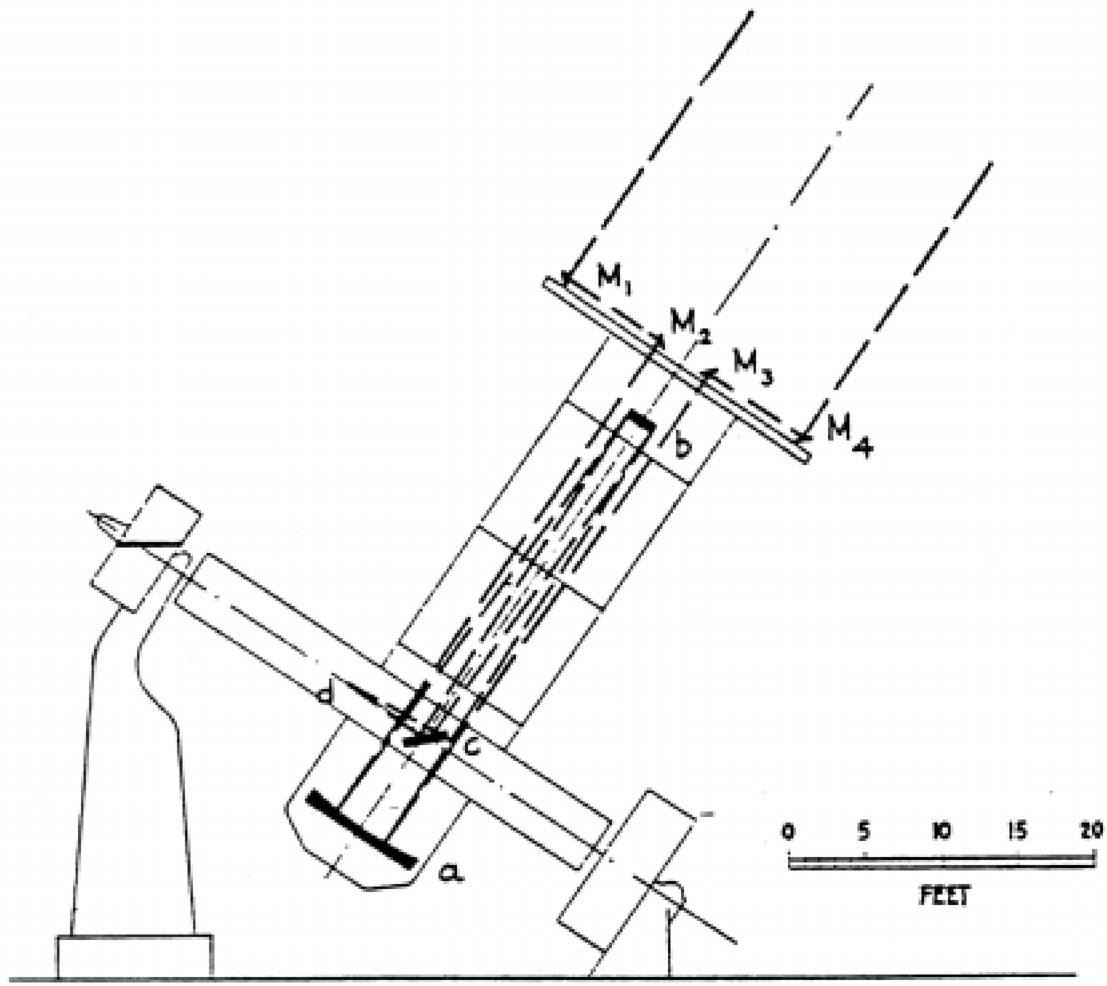


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

One of the wedges (H, Fig. 3), whose angles are about 10°, can be moved 25 mm either side of its mean position, parallel to the inclined surfaces. One turn of the rod (J, Plate IVb) shifts this wedge 0.5 mm, thus introducing an equivalent air path of about 0.045 mm. Although fringes can be observed throughout one-third of a turn, corresponding to an air path of 0.015 mm, or about 26 light-waves, the finding of the fringes is notably facilitated by a direct-vision prism (K, Plate IVb) placed in front of the eyepiece, which permits observation of interference bands with a path-difference of several hundred waves.

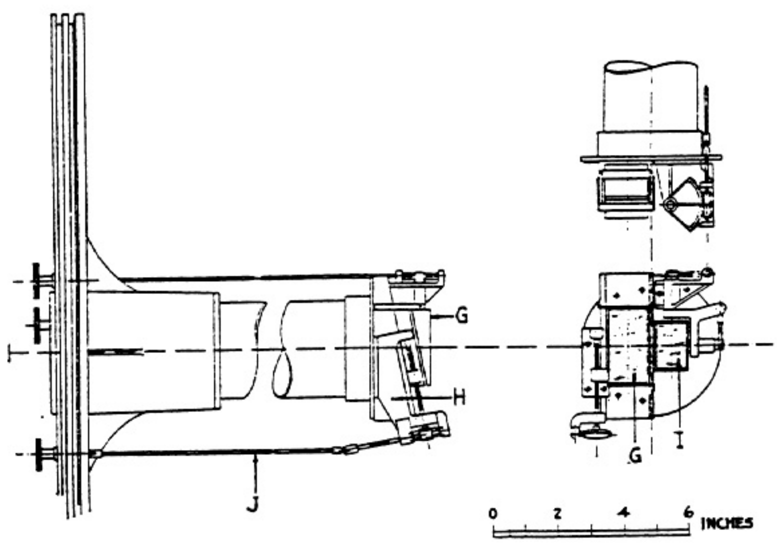


FIG. 3.—Diagram of adapter at focus. G, fixed wedge; H, movable wedge; I, plane-parallel compensator; J, rod to shift wedge.

To obtain a series of reference or "zero" fringes the end of the telescope tube is entirely covered, save for two apertures in the beam (in addition to those of mirrors M_2 and M_3), 6 inches (152 mm) in diameter. The pencils entering these apertures pass through the wedges and the compensating plate, respectively, and produce an image of the star in the field of view. When adjusted for coincidence and equality of path, these pencils interfere and produce the zero fringes which cross the reference image.

The interferometer images are next brought into the field of view of the eyepiece and made to coincide a short distance from the zero star, thus forming a second star in the field of view. Usually the adjustment of the mirrors M_1 and M_4 is sufficient to do this and the parallel plate compensator is used only for differential deflection

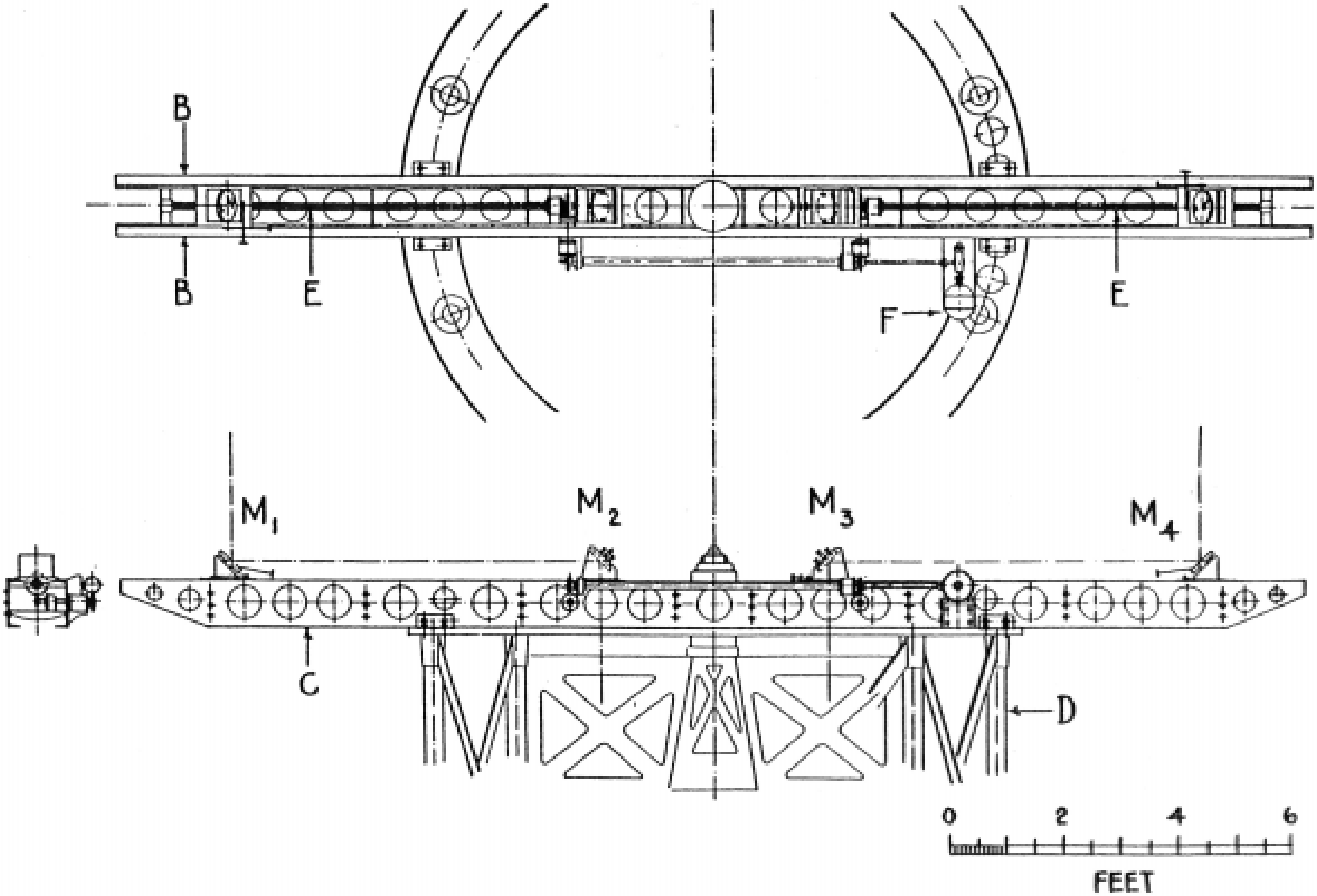


FIG. 2.—Diagram of 20-foot interferometer beam. M_1, M_2, M_3, M_4, mirrors; B, B, 10-inch channels; C, steel plate; E, E, screws to move outer mirrors; F, motor drive for screws; D, Cassegrain cage.

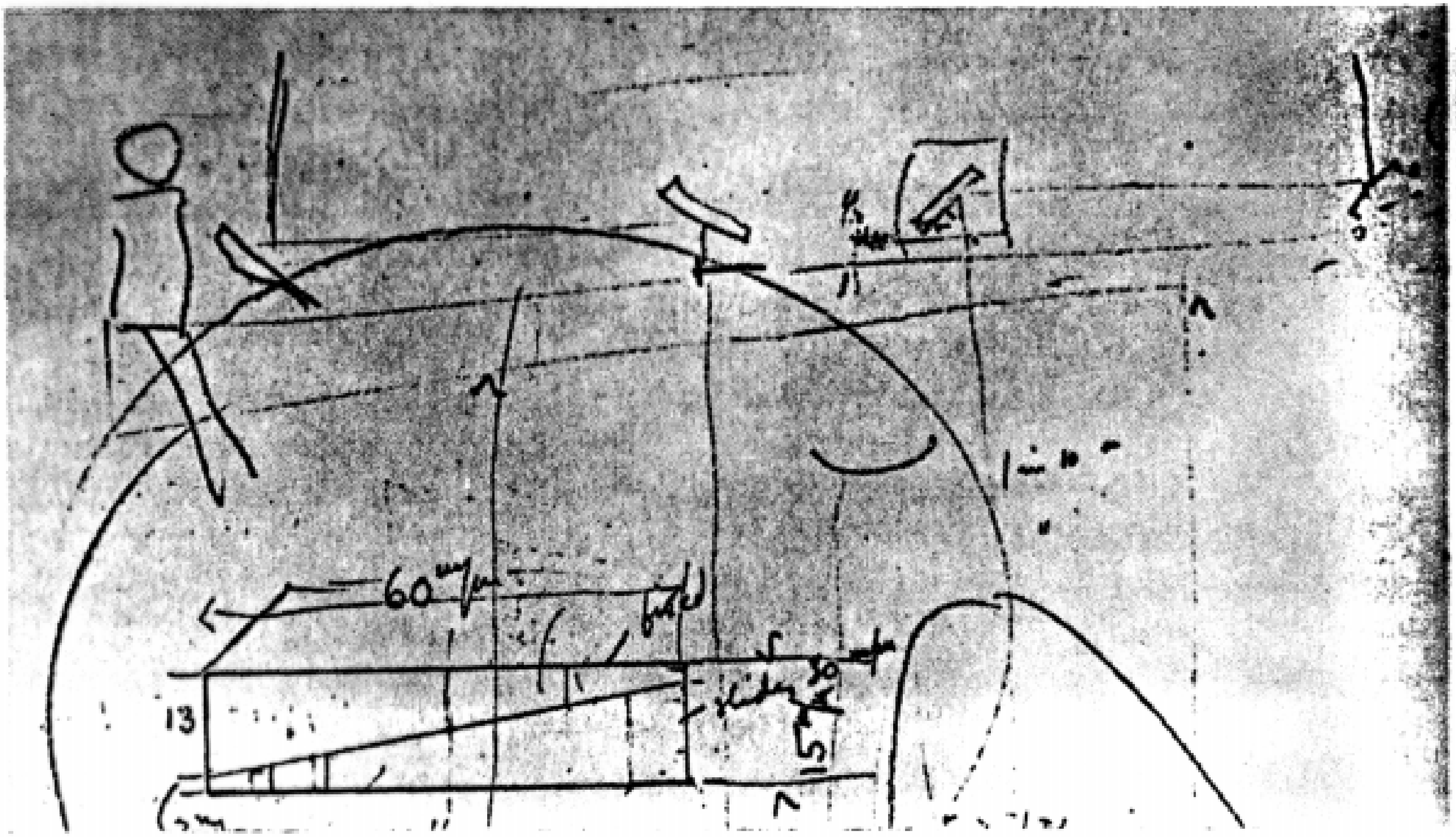


FIG. 3. From F. G. Pease, Notebook 1, sheet 42; approximate date 14 July 1920 (Hale Observatories, copy in Michelson Museum). Crude drawings of the optical wedge used to equalise path length. Note the superimposed sketch illustrating how the night assistant must be perched to move the mirrors on the beam. This situation was necessary because the mirrors, at first, were not continuously adjustable.

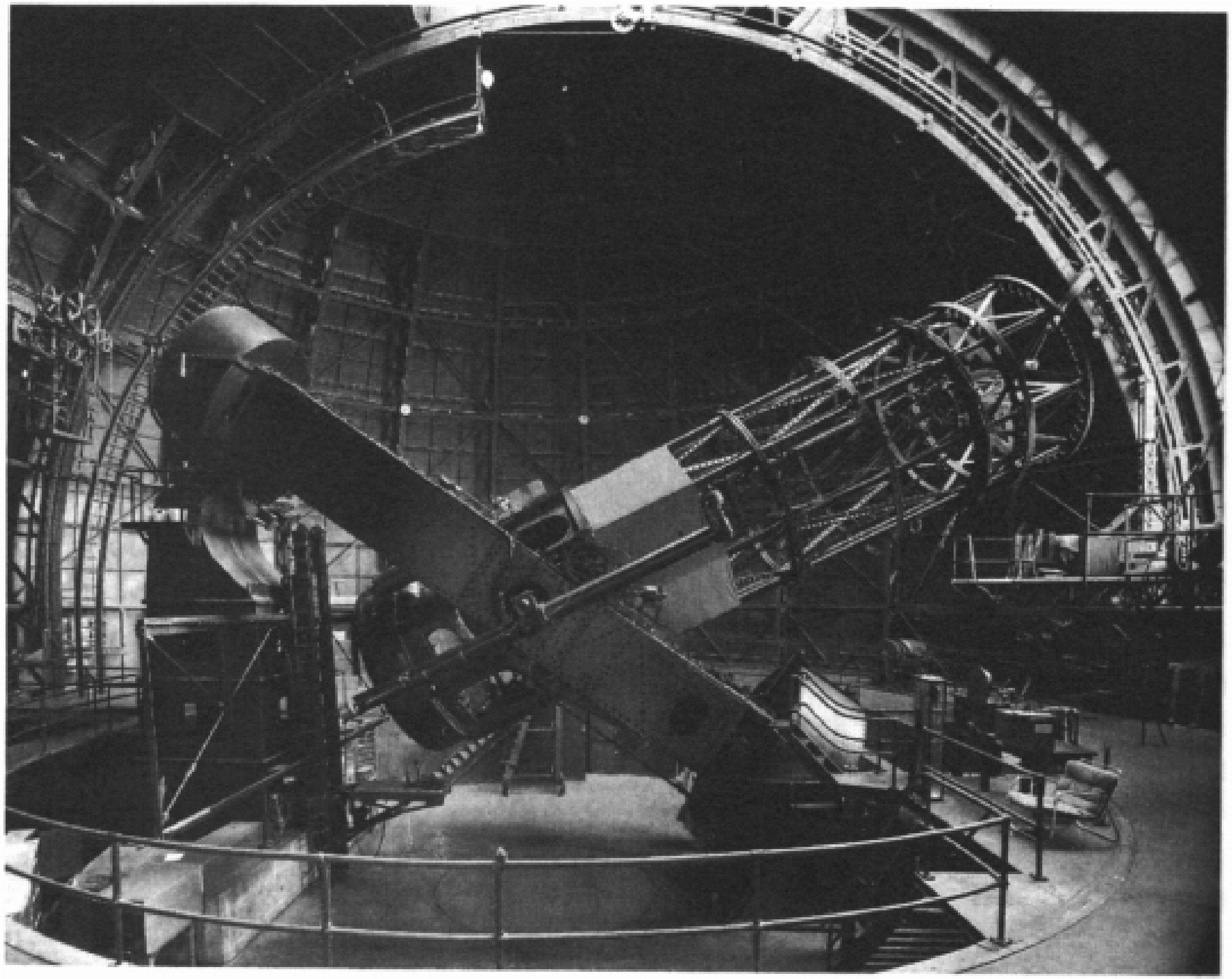
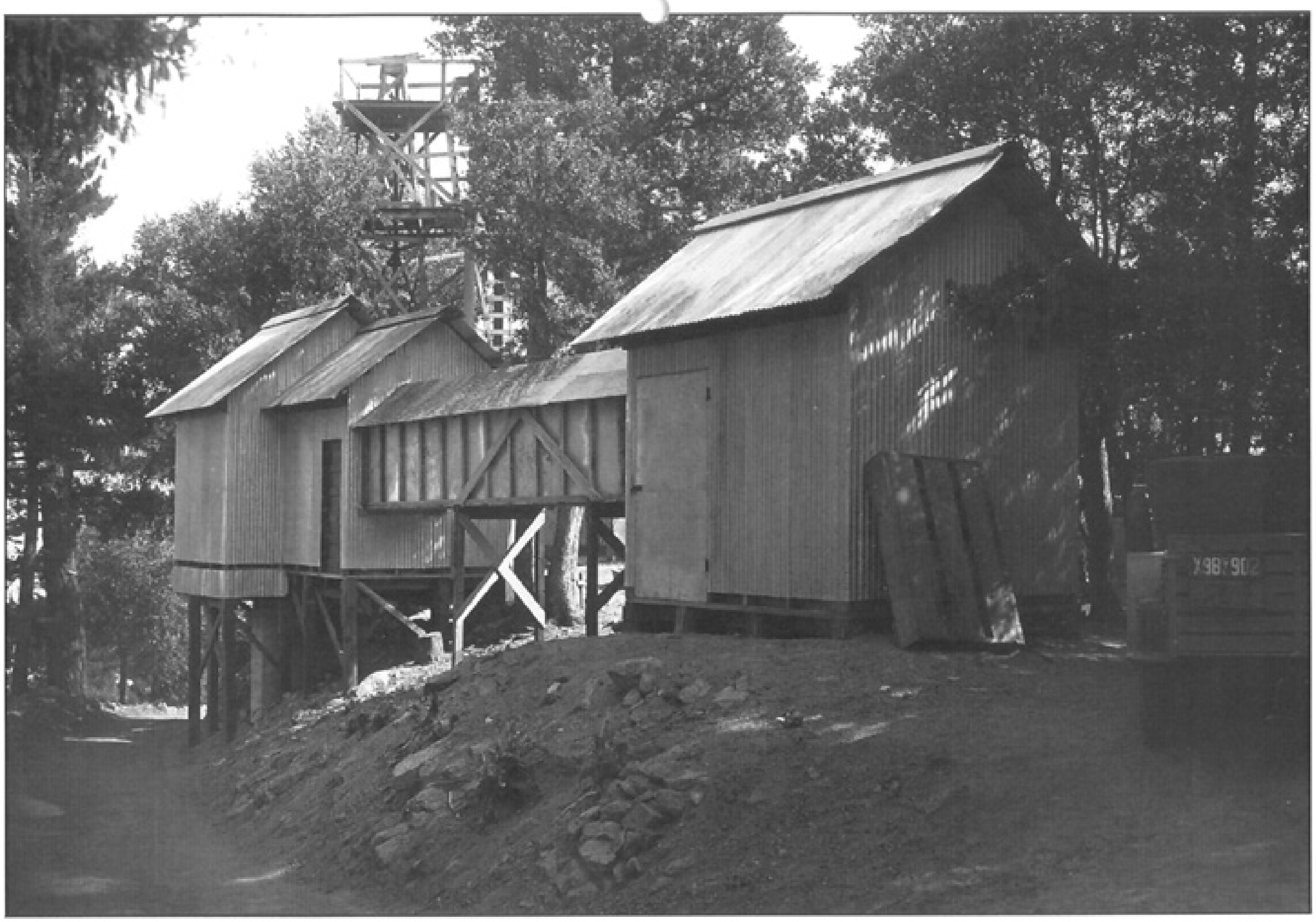


Figure 13.5 *The 100 inch (2.5 m) Hooker reflector on Mount Wilson, completed in 1917. (Courtesy* The Observatories of the Carnegie Institution of Washington.*)*

Albert A. Michelson, about 1928



Michelson's Mount Wilson Speed-of-Light Facility

This May 1929 photo shows the Mount Wilson facility used by Albert Michelson (1852-1931) from late 1924 to early 1928. An arc light beam was sent eastward 22 miles to near "Old Baldy" and reflected back to Mount Wilson. A rapidly rotating polygonal mirror placed in the light path had its rotation adjusted until two successive faces of the mirror were in just the correct position to reflect the light out and back to its origin. This rotation rate determined the time taken for the beam to complete the two- way trip. The speed of light directly followed from this travel time and the known distance. The cement pier under the leftmost building still stands today with a memorial plaque just north of the Telescopes in Education 24-inch dome. Some trees seen here are still growing.

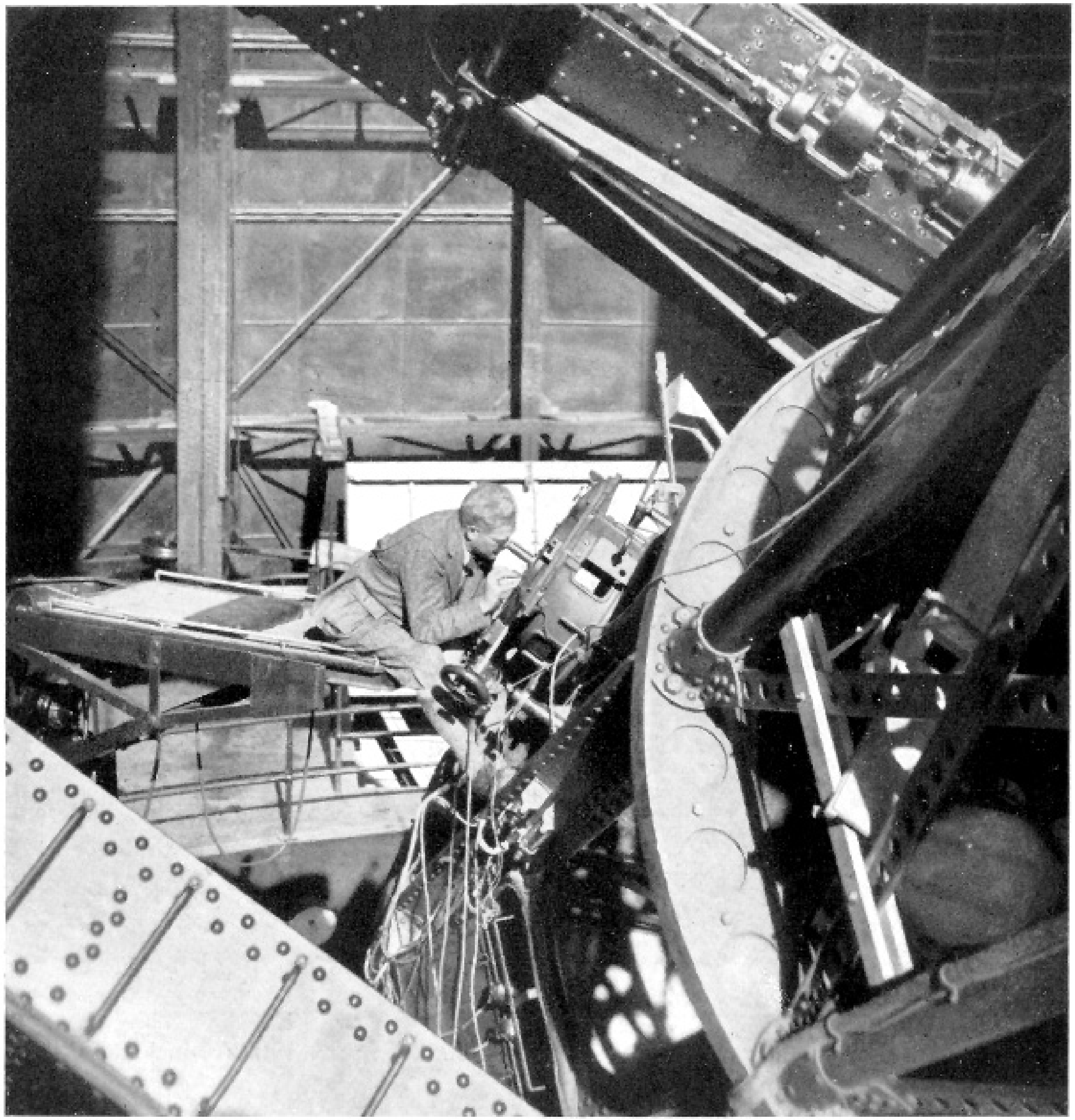
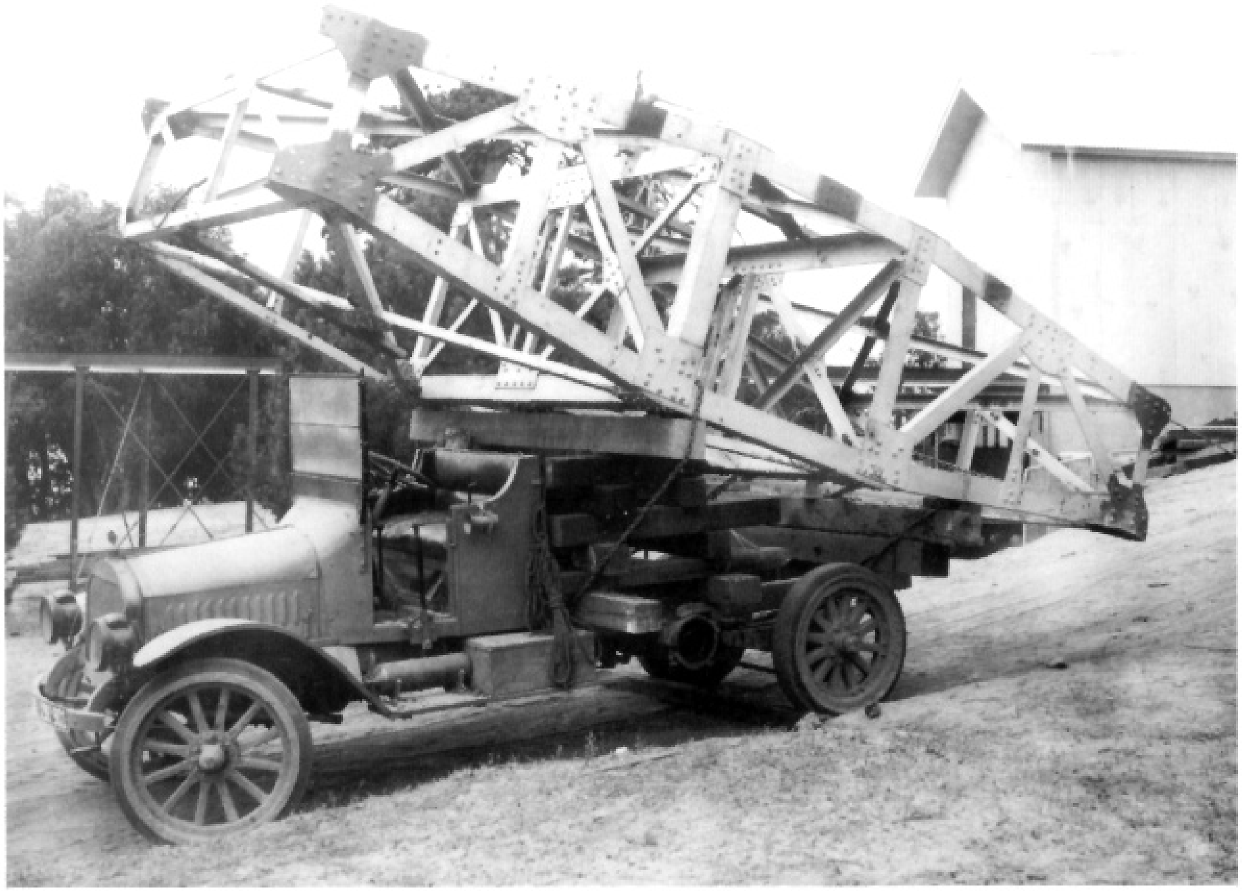


Abb. 3. Showing observer at eyepiece of 20 foot interferometer.



Arrival of Central Section of 50-foot Interferometer Beam

A 50-foot optical interferometer was built in the late 1920's in an attempt to gain the longer baseline needed for high spatial resolutions. This photo shows the main section of the 50-foot beam upon its arrival at the observatory. The "50 footer" never lived up to its promise, but in 1986, the Navy built its Mark III Optical Interferometer on Mount Wilson with a 44-foot baseline in 1986 and a 103-foot baseline in 1988. The Georgia State University optical interferometer with a 1000-foot baseline is expected to see first light on Mount Wilson in 1998.

Abb. 5. 50 foot interferometer seen from the North.

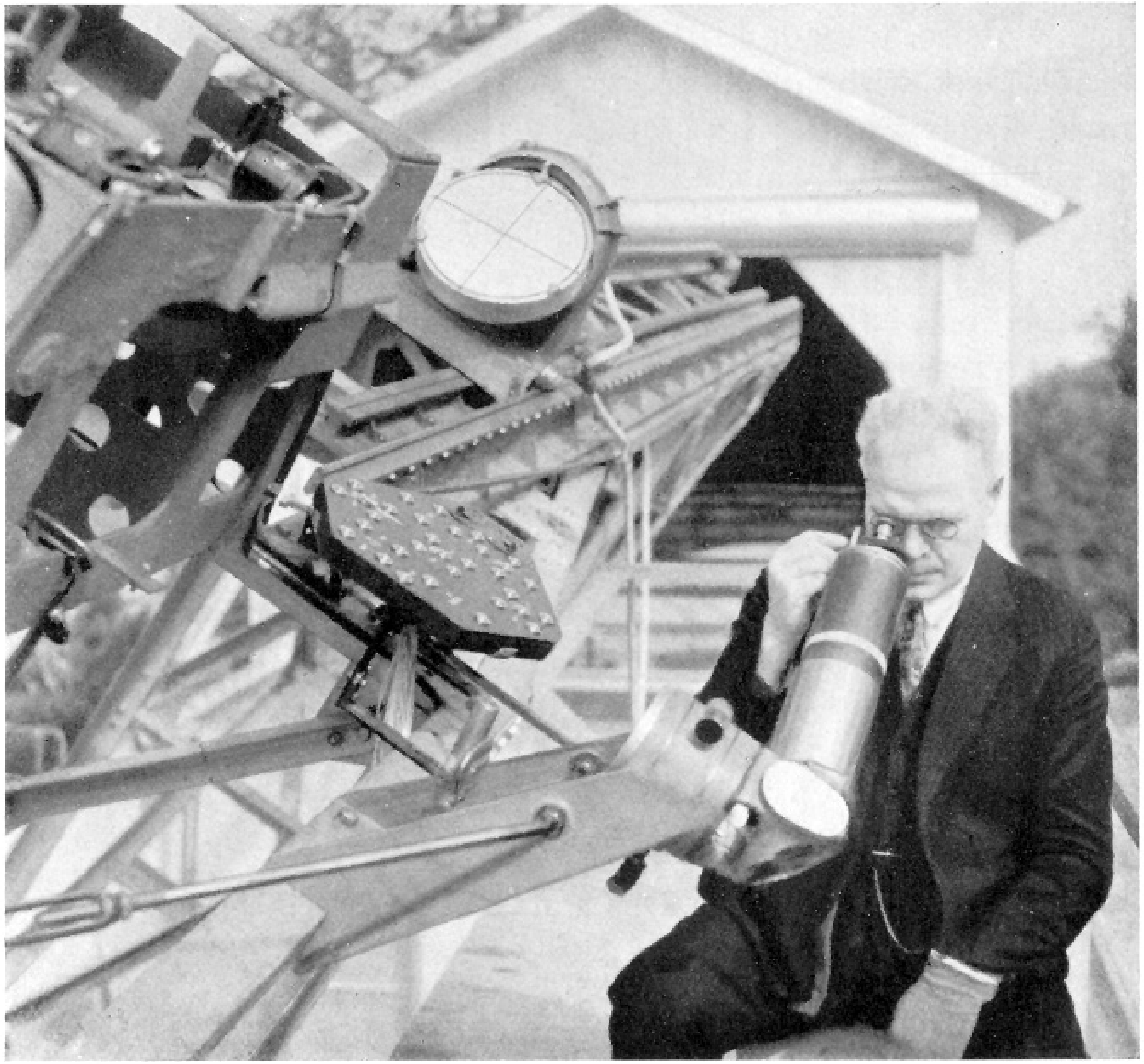


Abb. 9. Upper part of interferometer showing control board and observer at eyepiece.

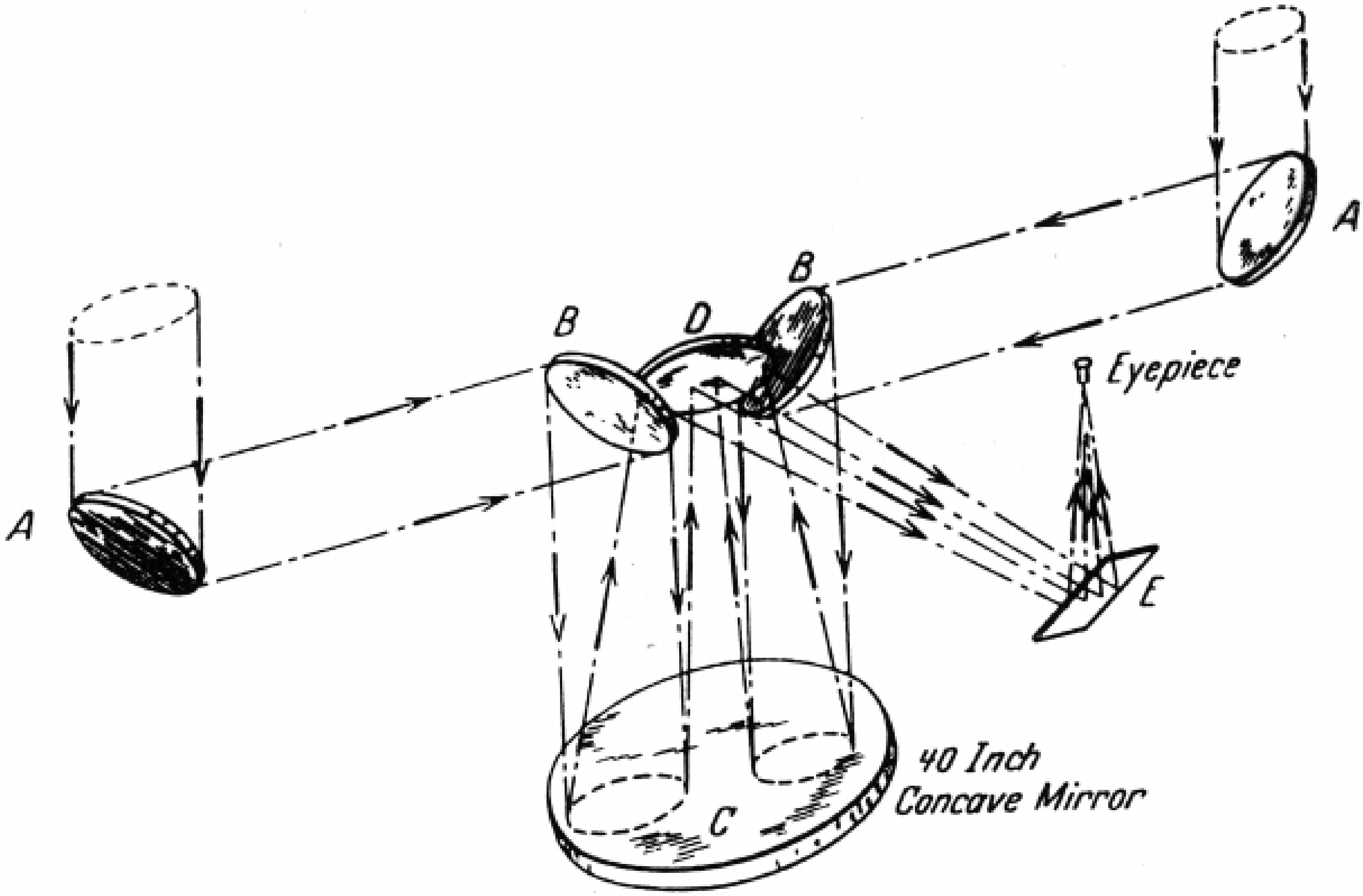


Abb. 8. Diagram of light path in 50 foot interferometer.

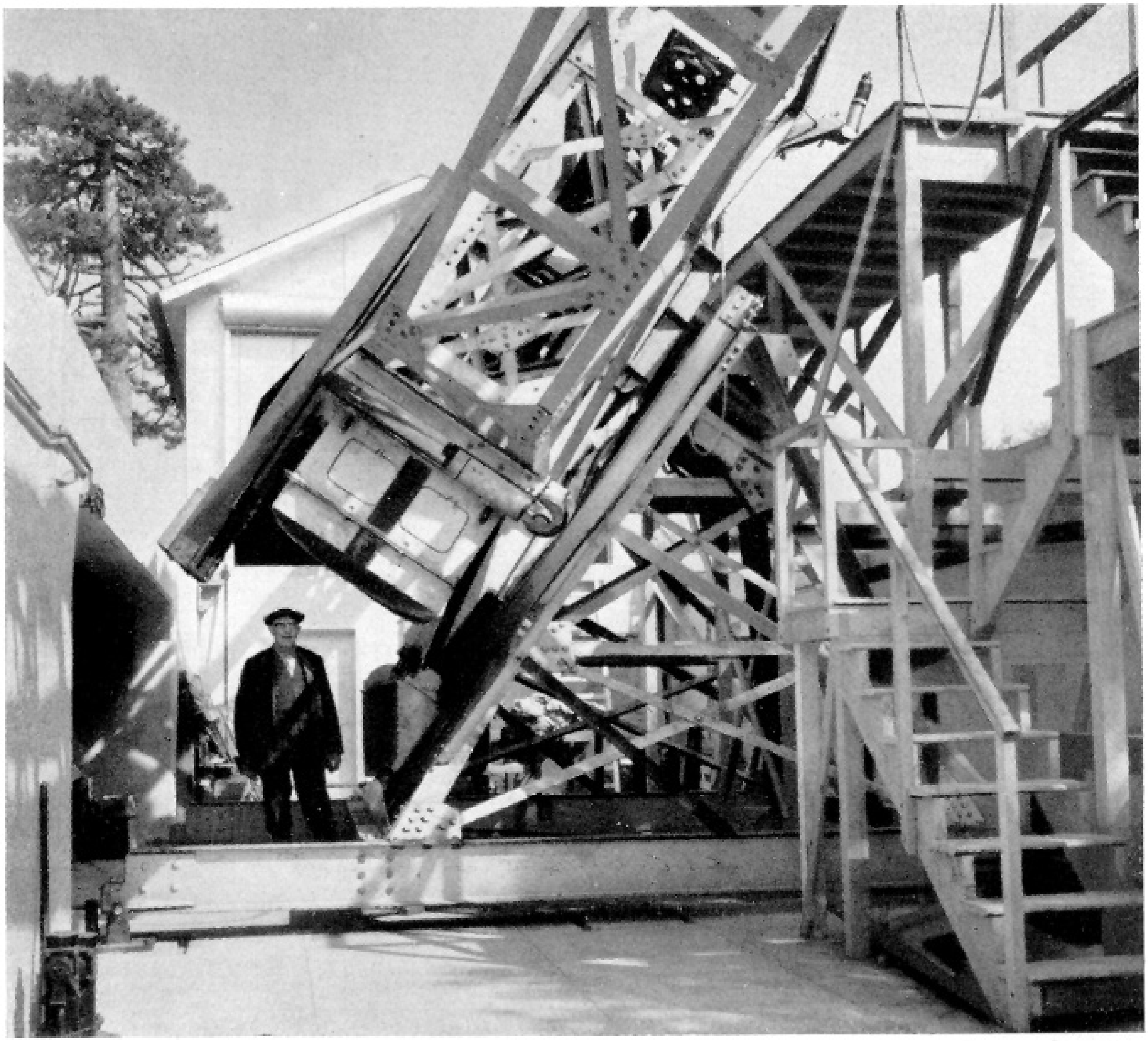


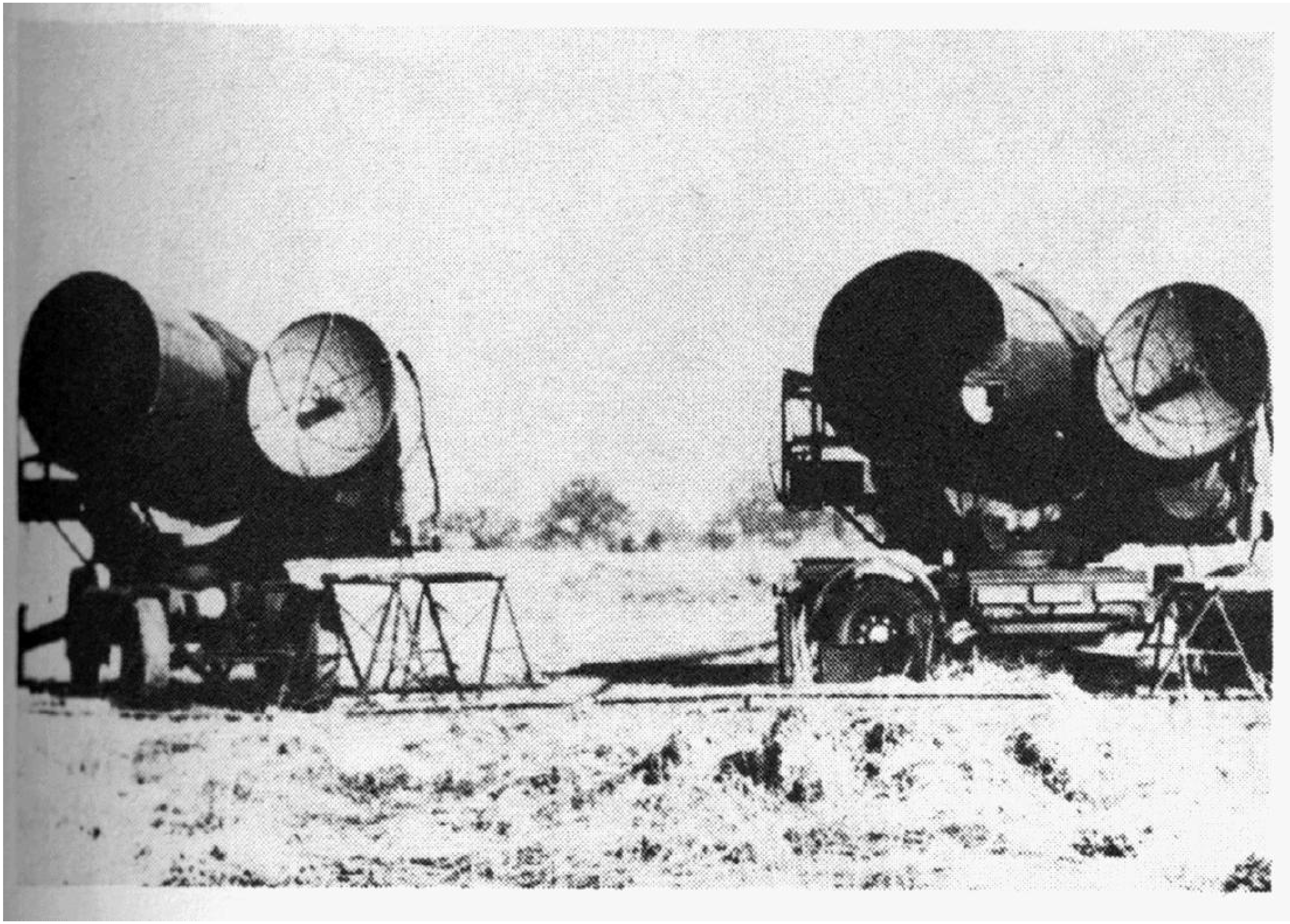
Abb. 7. The 50 foot interferometer showing pedestal, mirrorcell and wormsector.

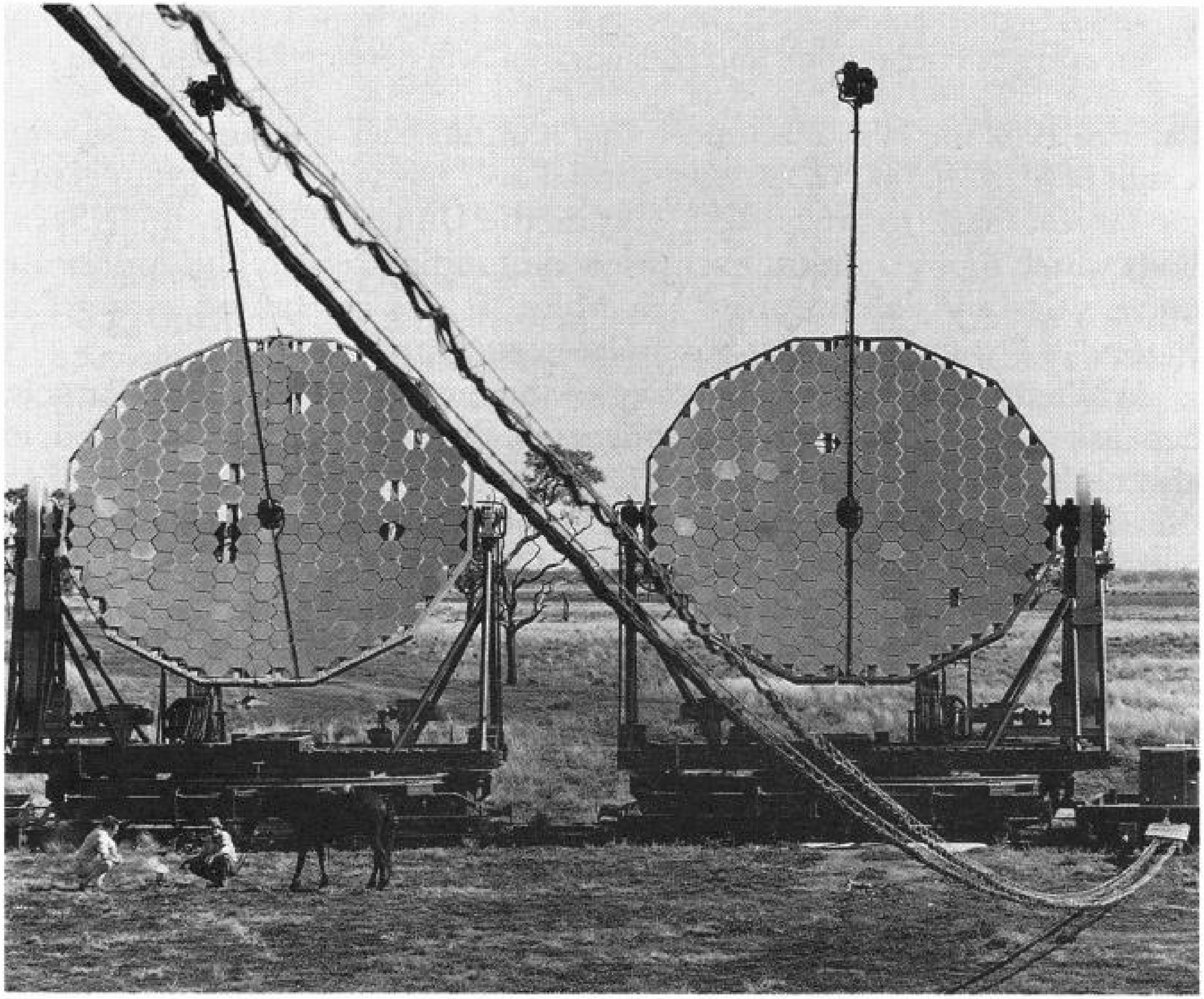
F.G. Pease (1881-1938)
50 ft Interferometer

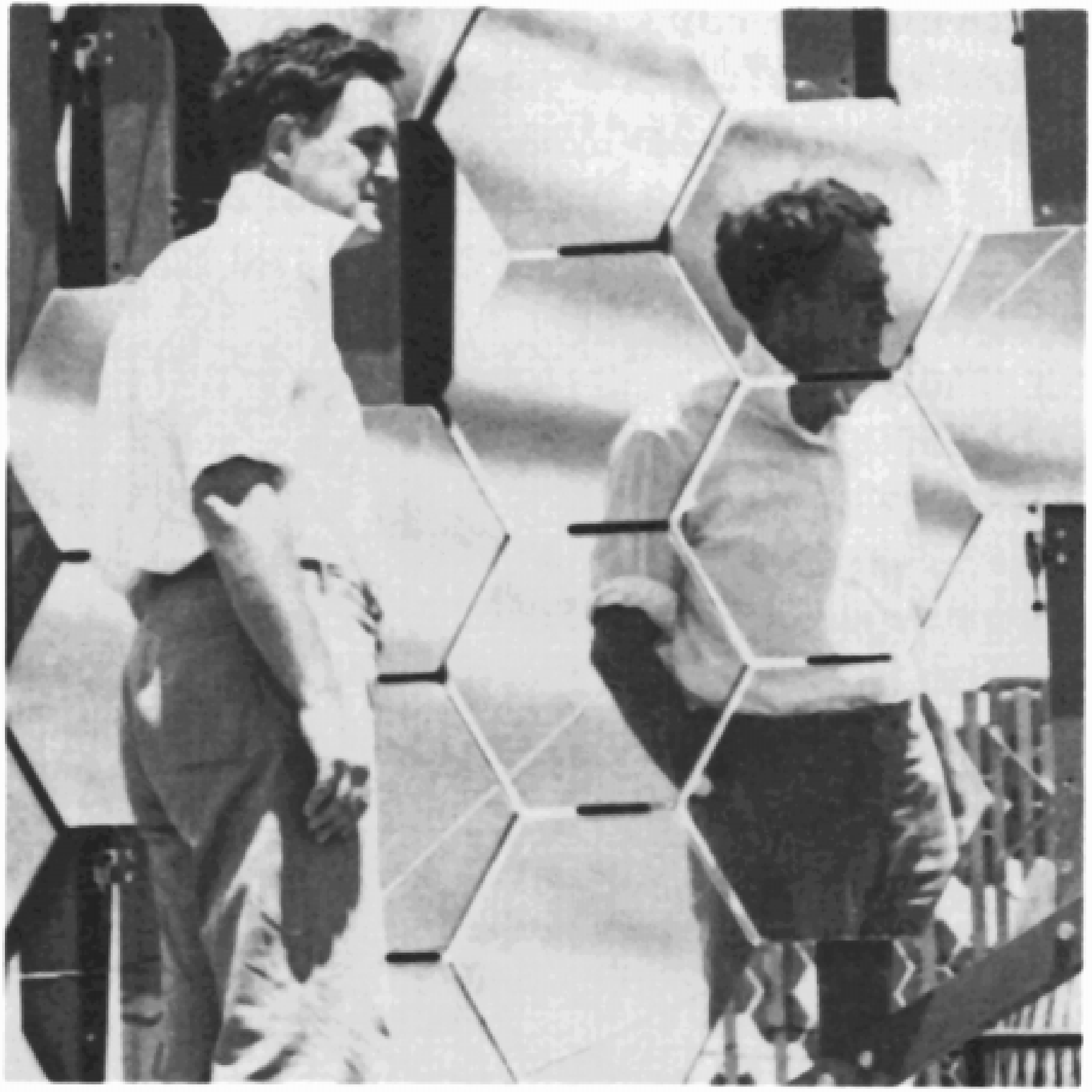
- Designed and built by F.G. Pease (1931).
- Stellar diameter estimates by looking for the baseline where fringes disappeared.
- Probably subject to numerous problems
  - 38 cm mirrors produced speckled images.
  - Increased fringe motion at longer baselines.
  - Excesssive vibrations.
  - Polarization mismatch between arms.
- Produced results of questionable value.
  - Accuracies estimated at 10 - 20%.
- Observations ceased in 1938.

Intensity Interferometer (1963-1972)

- **R. Hanbury Brown and R.Q. Twiss (1956).**
- **Diameter of Sirius estimated from experiments at Jodrell Bank, UK (1956).**
- **Manchester University and Sydney University build the *Intensity Interferometer* at Narrabri, NSW, Australia (starting 1961).**
  - **Initially under the guidance of Twiss**
  - **Hanbury Brown established as Professor at Sydney University**
- **Measures 32 stars to a limiting magnitude of B=+2.5, spectral types O-A inclusive, and accuracies of 1 or 2%.**
- **Measures orbit of Spica (α Vir)**







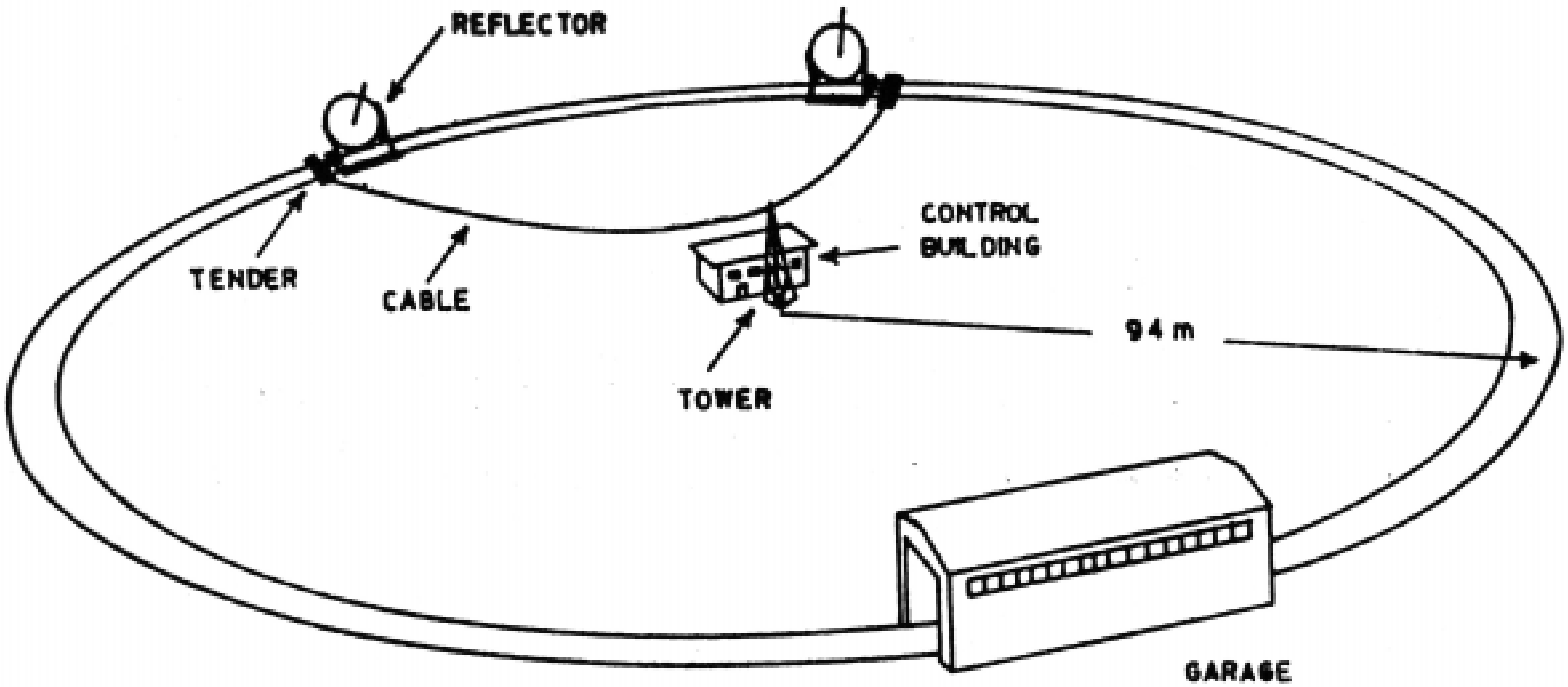


FIG. 7. The general layout of the interferometer at Narrabri Observatory.

Direct Detection Interferometry in the 1960s

- **W.I. Beavers , "Modern Stellar Interferometry"** *Astron. J.* **68 (1963)**
- **R.H. Miller, "Measurement of Stellar Diameters"** *Science* **153 (1966)**
- **1967 Woods Hole Summer Study on "Synthetic Aperture Optics"**
  - **Advisory Committee to the Air Force Systems Command**
- **D. Currie and the University of Maryland (1967)**
- **H.A. Gebbie, R.Q. Twiss, W.J. Tango and the Monteporzio Interferometer**

Antoine Labeyrie
The I2T and GI2T

- Speckle interferometry invented 1970
- First fringes with separated telescopes at the Observatoire de Nice (1974)
- I2T is moved to CERGA (1976)
  - Moving optical table as delay line
  - No tilt correction
  - Visual fringe estimates till 1984
  - Only long-baseline amplitude interferometer measuring *stellar diameters* up until 1985.
- GI2T obtains first fringes (1985)
  - Logical extension of the I2T

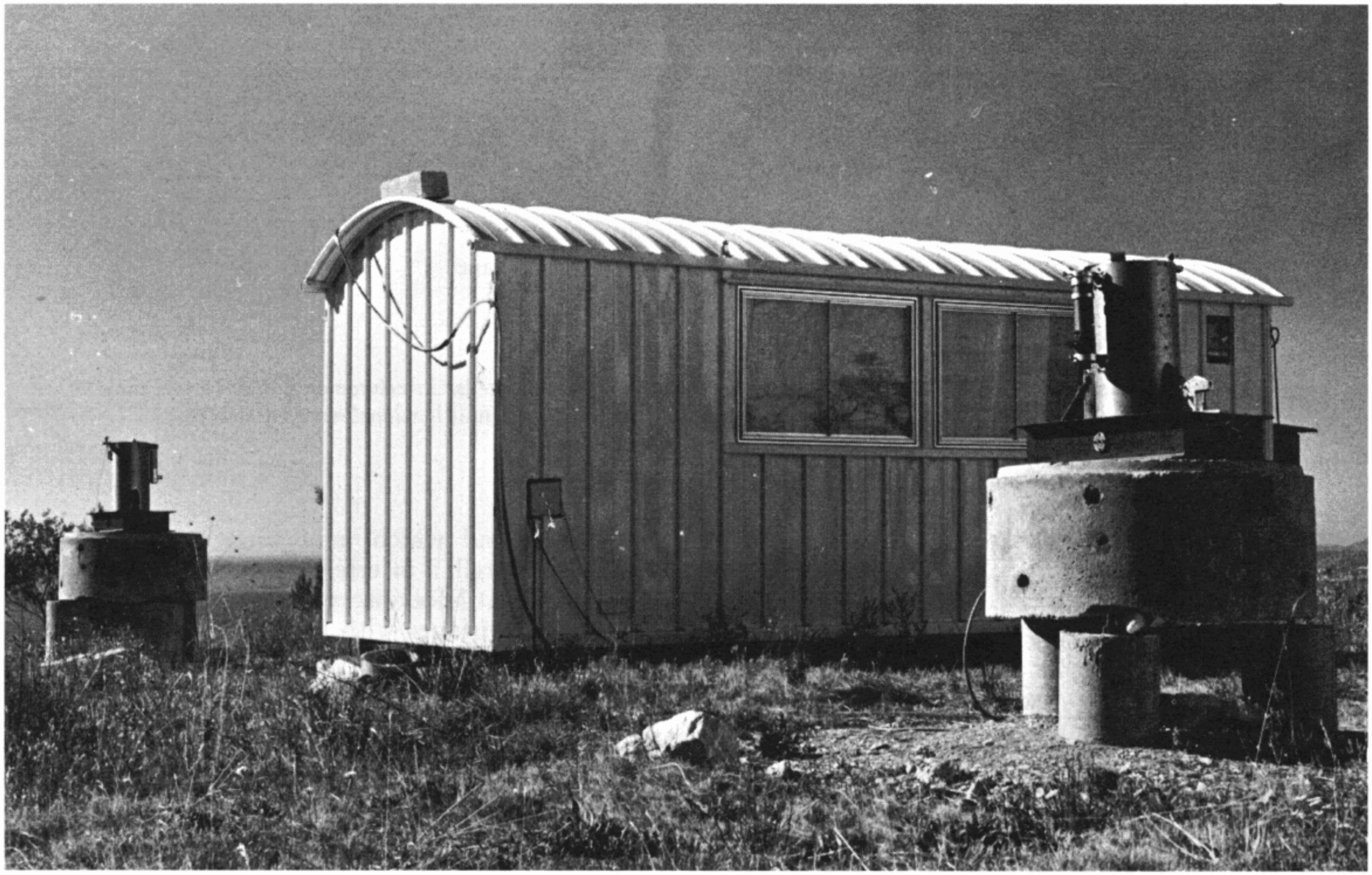


FIG. 2.—Interferometer at Nice observatory, showing the heavy alt-alt yoke mounts with their servo drives. The large concrete elements are commercial pipe sections providing a stable but movable substrate. Not visible is a mechanism which rotates the coudé mirror at half the declination rate, thus providing a fixed coudé output. The construction of 60-m tracks is currently undertaken for a variable baseline.

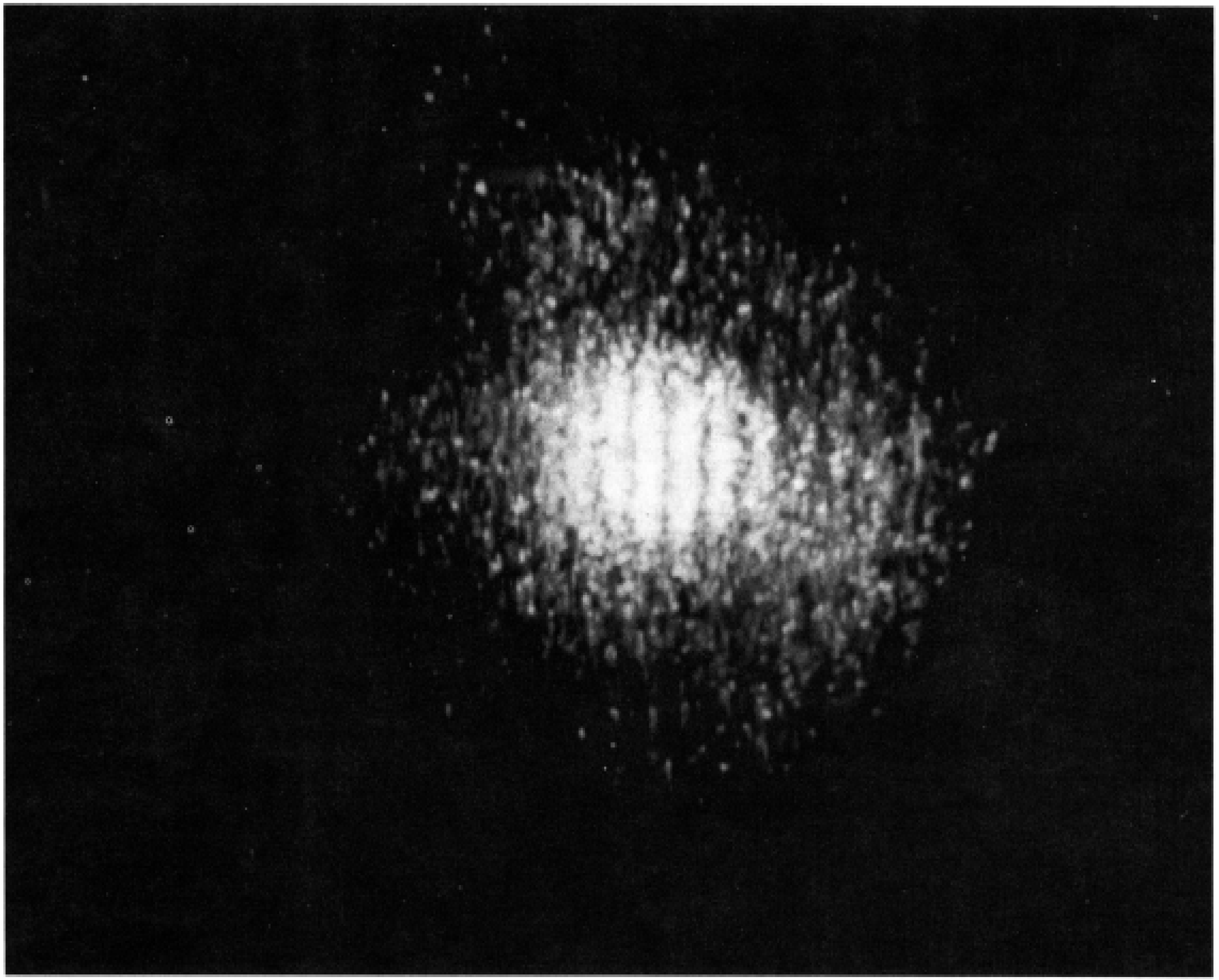


Fig. 4.—Interference fringes (photographed from a television sequence), obtained in the image of Vega with 500 Å bandwidth. In this case, the photon-counting camera is operating at reduced gain in the analog mode. Individual photon events are nevertheless visible as bright points.

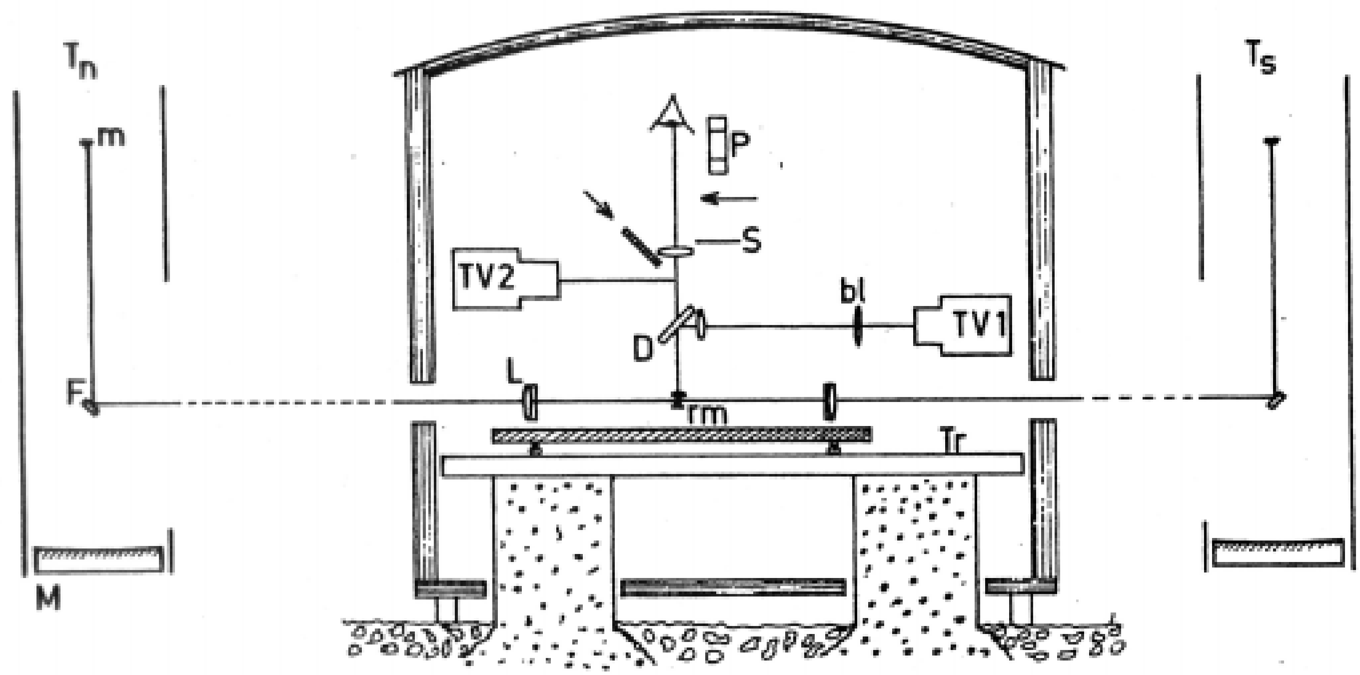


FIG. 1.—Optical layout of the two-telescope interferometer: Tn,Ts: north and south telescopes; M: 250-mm primary mirror (f = 850 mm); m: Cassegrain secondary (f = 7.5 mm); F: coudé flat; L: field lens; rm: roof mirror in pupil plane; D: dichroic mirror; TV1: guiding camera; bl: bi-lens serving to separate the two guiding fields; S and P: slit and direct view prism used for fringe acquisition; TV2: photon-counting camera (tunable filter not represented); Tr: tracks on which table moves (programming mechanism not represented).

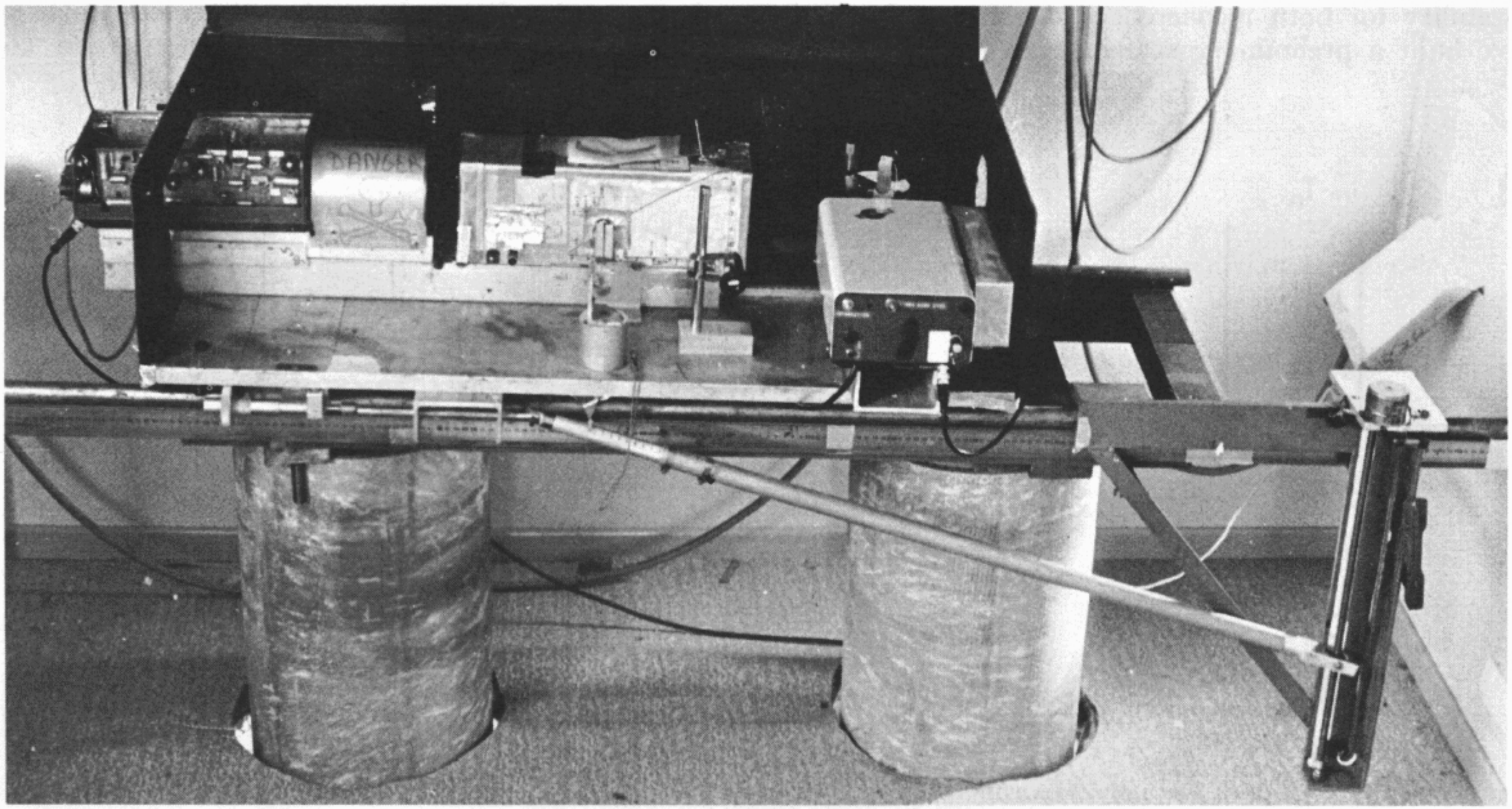


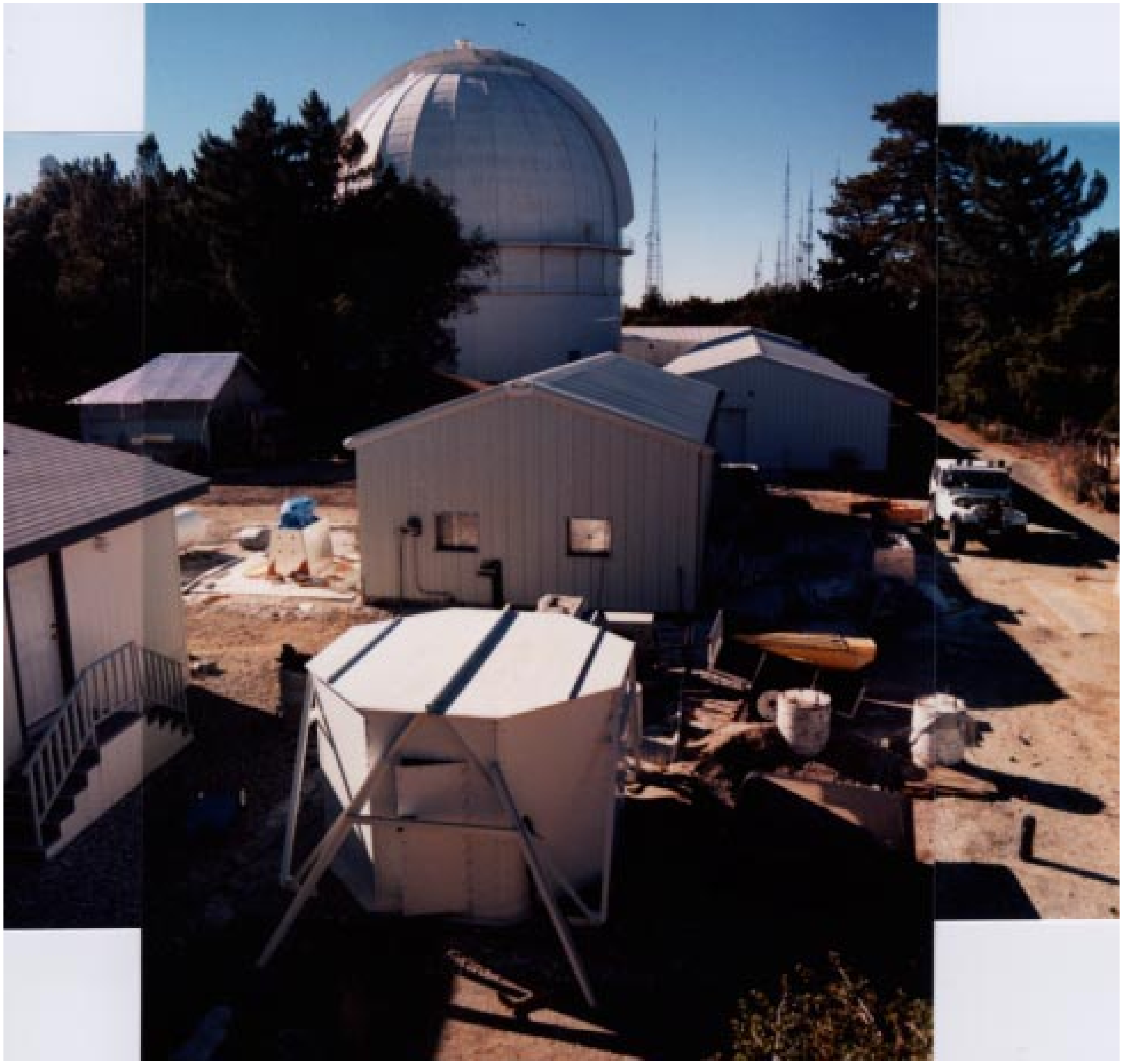
FIG. 3.—Central station, showing the optical table with its tracks, and the fringe-tracking mechanism which approximates the required cosine H displacement law. The concrete piers independent from the building are also visible, as well as the micrometer screw which allows for fine fringe tracking.

Amplitude or Intensity Interferometry?

- Continuation of program beyond the Intensity Interferometer - dismantled 1976.
- Sydney University 11.4 m Prototype Interferometer (1981-88) based on experience from the Monteporzio Interferometer.
- Sydney University Stellar Interferometer:
  - Baselines out to 640 m to measure hot O-type stars at blue wavelengths.
  - Accuracy of better than 2% desired in angular diameter estimates.

Astrometry with the Mark I, II, and III

- **Mark I**: Phase tracking stellar interferometer built by M. Shao and D.H. Staelin (1977-79)
  - Tilt correction + phase tracking.
  - No delay line.
- **Mark II**: Technology testbed for astrometry
  - High speed delay line implemented.
  - Star-switching automated.
  - Astrometric interferometry demonstrated
- **Mark III**: First fringes in 1986.
  - Astrometric accuracy of 10 to 20 milliarcseconds.
  - Modified for longer baselines (up to 30m) and stellar measurements by NRL/USNO.
  - Extensive list of publications.



A site had been selected on a piece of land 6 miles southwest of the town of Santa Ana. This property had originally been part of an enormous Spanish land grant. Its owner, James Irvine, Jr., generously allowed the observatory to use part of it. The terrain was well suited to Michelson's purpose, varying only a few feet in elevation over the distance of a mile.

A $50,000 contract had been drawn up with the California Corrugated Culvert Company to furnish the 36-inch steel pipe in 60-foot lengths. Fred Nichols, a capable engineer on the Mount Wilson staff, had worked out the electrical circuit and devised an original manner for sealing the pipe at each joint with the inner tube of a tire covered with several coats of rubber paint.

FIG. 102. A general view of historic Poulkovo Observatory. The revolving turret of the 15-inch refractor appears in the center.